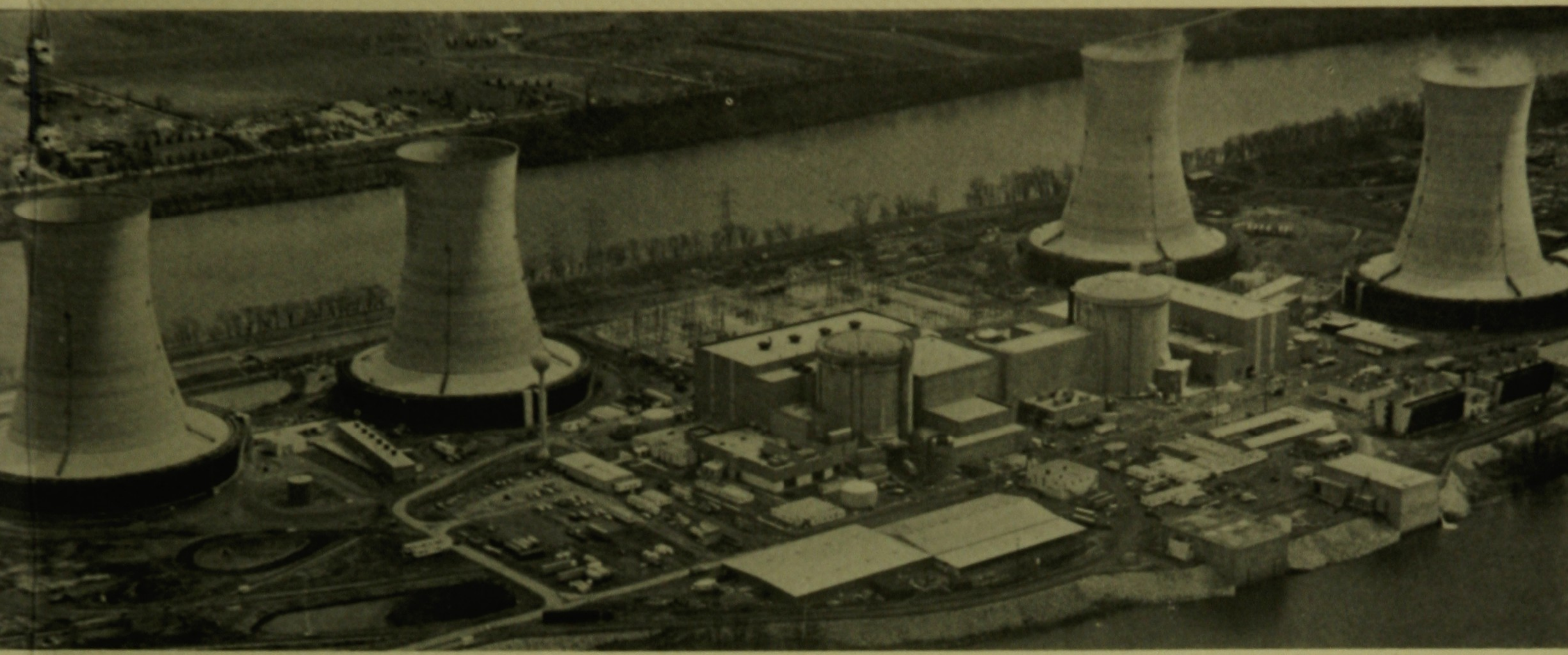
GEND-INF- 068
September 1985



This is an informal report intended for use as a preliminary or working document

GEND

General Public Utilities • Electric Power Research Institute • U.S. Nuclear Regulatory Commission • U.S. Department of Energy

TMI-2 CABLE/CONNECTIONS PROGRAM

FY-85 STATUS REPORT

Richard D. Meininger
Donald R. Chick
Collins P. Cannon
Merlin E. Yancey
Mike R. Dinsel
Florante T. Soberano

Prepared for the
U.S. Department of Energy
Three Mile Island Operations Office
Under DOE Contract No. DE-AC07-76ID01570

GEND-INF-068

TMI-2 CABLE/CONNECTIONS PROGRAM
FY-85 STATUS REPORT

Richard D. Meininger
Donald R. Chick
Collins P. Cannon
Merlin E. Yancey
Mike R. Dinsel
Florante T. Soberano

Published September 1985
Idaho National Engineering Laboratory

EG&G Idaho, Inc.
Idaho Falls, Idaho 83415

Prepared for the
U.S. Department of Energy
Three Mile Island Operations Office
Under DOE Contract No. DE-AC07-76-IDO1570

ABSTRACT

This report documents the continuing effort by the Department of Energy to determine the condition of electrical circuits within the reactor building at Three Mile Island Unit Two (TMI-2) as affected by the accident of March 28, 1979. GEND-INF-056 TMI-2 Cable/Connection Program FY-84 Status Report (in situ test phase) is background for this report, listing each circuit by penetration and giving the respective end instrument or device. GEND-INF-056 also presents sketches of each circuit path.

This report further considers anomalies in the electrical circuits located in the reactor building based on the in situ test data and relates them to physical anomalies, known or implied. Since the anomalies vary in degree of severity, the number of circuits with anomalies is not meaningful without an explanation of the anomalies. This report presents tables of the anomalies. The circuits have not been physically inspected to date, so conclusions cannot be rendered or verified for all circuits.

This report also presents the results of laboratory tests on cables and terminal blocks. The tests measured the variation in the cable parameters for various test conditions, including a dry and wet cable, a cable looping in a cable tray, cables inserted into a dry and water-filled conduit, and a cable terminated with a terminal block submerged in water.

However, because the TMI-2 test data were acquired with transmitters and other active devices in their unpowered state, the operational status on many circuits could not be verified. An evaluation of the available TMI-2 plant cable test data indicate that 3.5% of circuits tested are nonfunctional.

CONTENTS

FIGURES

TABLES

TMI-2 CABLE/CONNECTIONS PROGRAM
FY-85 STATUS REPORT

INTRODUCTION

Shortly after the March 1979 accident at Three Mile Island Unit 2 (TMI-2), the U.S. Department of Energy became involved in research related to the event and established the Technical Information and Examination Program (TI&EP) to assist in solving technical cleanup challenges and to collect, analyze, and document data that would benefit nuclear power plant safety. An important part of the TI&EP is the Instrumentation and Electrical (I&E) Program. In 1981, I&E personnel initiated a major cable analysis effort, called the Cable/Connection Program. This effort supports accident prevention and mitigation philosophy by establishing the physical limitations and performance of interconnecting cables for instrumentation and electrical equipment exposed to an actual loss-of-coolant-accident (LOCA) environment. Examination, testing, and analysis will provide data for better evaluation of reliability, aging, and performance, and for improvements in the design, manufacture, and installation of instrumentation, electrical equipment, and cable systems equipment.

The components and cable systems in the TMI-2 reactor building were exposed to varying degrees of radiation, steam, humidity, reactor building suppression and gross decontamination sprays, submergence, a hydrogen burn event, and a post-LOCA environment. Study of the electrical and physical properties of selected cable system components will allow assessment of how the cables and connections responded to these accident environments.

In fiscal year 1984, GEND-INF-056, titled <u>TMI-2 Cable/Connection Program FY-84 Status Report</u>, was issued[1]. It described the environment inside the reactor building where the circuits evaluated in this report were located. It also listed the cables tested and showed their locations. It described the tests made on the circuits and preliminary assessments of the circuits.

This report updates the environmental conditions for TMI-2 that were given in Reference 1. It reviews the circuits tested and the tests made on them. Before considering the data from TMI-2, some laboratory measurements are presented. In order to simulate the possible wet cables of TMI-2, water was injected between the jackets and conductors of cable samples from TMI-2. Test measurements were then taken on the wet cables and compared with data obtained from dry cables. Tests were also made to evaluate the effects of cables on cable trays and in dry and water-filled conduits. The tests also measured the electrical effects of wetting terminal blocks.

The next section describes anomalies in the TMI-2 test data that indicate degradation of the circuits. Each type of anomaly is described, and tables are given that list the circuits found to have each type of anomaly.

The last section develops methods to evaluate the functional conditions of the circuits and uses these methods with the in situ TMI-2 data. The circuits are evaluated in functionally similar groups, and results are thus tabulated.

OBJECTIVES

In fiscal year 1985, the I&E program evaluated the in situ measurements for anomalous behavior that would indicate degradation of the circuits and components. The evaluation attempted to determine the functional condition of the various circuits and identify the locations and probable causes of failures. A common analysis method was used on circuits having similar driving devices, terminations, and functions.

Another objective of the program was to perform laboratory tests on samples of TMI-2 cables, which would simulate expected types of degradation, and note the effects of known degradation on the test measurement. This testing provided a baseline for evaluation of the TMI in situ test data.

ENVIRONMENTAL CONDITIONS

During the first day of the accident, the environment inside the reactor building was one of intense radiation, steam, moderate temperature excursions, and a hydrogen burn resulting in a pressure spike that initiated a chemical suppression spray.

Steam and radioactive reactor coolant were discharged into the building through the reactor coolant drain tank rupture disc. The steam rose from the basement through the open stairwell to the upper levels. The release of water and steam resulted in an average air temperature increase of about 31°F during the initial hours after the accident. Components directly in the steam path experienced higher temperatures.

A total of approximately 600,000 gallons of water accumulated in the basement and may have possibly reached a maximum level of approximately 8.3 ft (291-ft elevation). Consequently, many instruments, electrical components, and cable trays were submerged. Because of the water in the basement and continuous operation of the air handling units, the relative humidity inside the reactor building remained at 100% for a period of two to three years.

Generally, the dose history, excluding the basement, consisted of high dose rates for a short time followed by relatively small dose rates for a long time. The estimated total integrated radiation dose varies with location and elevation. Radiation levels at the 282-ft elevation (the reactor building basement) currently are 20 to 40 R/h in most accessible areas with a peak of 1200 R/h near the air coolers. This relates to a maximum estimate total integrated dose of 10^8 rads. The integrated dose on the 305-ft elevation has been estimated at 10^5 rads, and the integrated dose at the 372-ft elevation has been estimated at over 10^6 rads.

The hydrogen burn occurred approximately ten hours after the start of the accident and resulted in a uniform increase in ambient temperature of approximately 81°F. It is believed that the hydrogen burn started in the basement, with flame propagation to the upper regions of the reactor building. The pressure spike that resulted from the burn activated the reactor building pressure suppression spray for about five minutes.

IN SITU MEASUREMENTS

Because entry into the TMI-2 reactor building was restricted and access to many measurement points was not expected to be available again, all types of measurements that might reasonably give useful data were made. It was believed better to take more data than may prove useful than than to possibly miss some pertinent information.

Test measurements were only performed on the reactor building portion of the circuit. Portions outside the reactor building were disconnected at terminal blocks or connectors located at various penetrations. Except as noted, all measurements in the reactor building were made with the end instruments or devices installed but unpowered. This caused problems in evaluating some circuits, but was necessary because access to the end devices was not practical due to the hazardous environment.

The various circuits tested were accessed through ten different penetrations and included the cables, connections, penetration and the terminating end devices. The circuits tested included 20 different types of cables and are often classed by the end devices which include heaters, motors, switches, relay contacts, transmitters, amplifiers, resistance temperature devices (RTDs), loose parts monitors, current transformers, and neutron detectors.

The following series of in situ electrical tests were performed on the various circuits located in the reactor building.

- Initial voltage characterization
- Time Domain Reflectometry (TDR) signature
- Capacitance
- Inductance

- Insulation Resistance
- dc loop resistance
- ac impedance
- ac resistance.

With the possible exception of TDR measurements, the tests were straightforward and are familiar to most electrical analysts.

Simplified, the TDR test is performed by transmitting a step voltage into the test circuit and observing the reflections that return to the sending instrument. These reflections occur at any change in characteristic impedance and, significantly, at any discontinuity or defect. The TDR test is a valuable tool for both identifying and locating defects in a cable.

Appendix A of Reference 1 describes the type of tests and test equipment used to perform the in situ testing. Data taking was automated, and data were stored on a floppy disc.

Initial voltage characterization was primarily made to prevent injury to the operator or damage to the instruments from unexpected high voltage. The voltage of each connection was measured before any other instrument was attached. Noise and power line pickup were noted if present.

Most dc loop resistance measurements were made with a Hewlett-Packard Model 3456A digital voltmeter.

Initially, capacitance and inductance were measured at 120 Hz, 1 kHz, and 10 kHz using a Hewlett Packard LCR Meter model HP4161A or HP4162A. Later measurements were made over the range of 100 Hz to 10 kHz in 100 Hz steps using an HP4192A LF Impedance Analyzer. For most analyses, the data at 1 kHz were used. The dissipation factor (D) and the quality factor (Q) were obtained for capacitance and inductance measurements respectively. Insulation resistance was measured between cable conductors and shield or to plant ground when there was no shield.

TDR data were obtained from a Tektronix Model 7854 storage oscilloscope with a 7S12 TDR sampler unit plug in. A Type S5 plug-in sampling head and a Type S54 plug-in pulse generator were used with the 7S12. Data from this TDR system allowed estimates of the propagation velocity and characteristic impedance to be made for the conductor pairs of the cables. TDR measurements have the advantage over other measurements because plots of the TDR data can also show certain discontinuities of electrical characteristics along the conductor pair tested, which can help to locate opens or shorts found by dc loop resistance measurements.

LABORATORY MEASUREMENTS OF ENVIRONMENTAL EFFECTS

In order to evaluate the environmental effects on the TMI circuits, two sets of laboratory measurements were made on various samples of TMI-2 cable types from unused stock. The first set of measurements were made on two cables to see what effects the cable trays, conduits, and water would have on the cable parameters. A second set of measurements was made of 15 different samples of TMI-2 cables in order to identify the effects of moisture on the cables' parameters. Measurements made on a wet terminal strip showed the effects on TDR data and some unique results with capacitance and conductance measurements.

Cable Tray and Conduit Tests

When unshielded cables (such as power cables) lay on metallic trays, resistive, inductive, and capacitive coupling between the cables' conductors and the cable tray cause the cable parameters to change. A similar effect occurs with cables in conduits. If the conduit is filled with water, even if the interior of the cable is dry, further effects on the cable parameters can be seen. Various tests were conducted on two cable types to identify, in general, the effects of these conditions. These tests were not made on each cable type because the magnitude of the effects would depend on placement of the cable with respect to the cable tray or conduit and the position of the other cables.

Water injected in a cable fills voids and displaces the air. Most cable insulation absorbs very little water, so filling of the voids is the predominant effect. Since the dielectric constant of water is about 78 and air is 1.0, the effective dielectric constant for a cable will increase. The amount of increase will depend on the percentage of void in the cable. As a result of the increase in dielectric constant, the capacitance will increase, the velocity of propagation will decrease, and the characteristic impedance will decrease. Since the permeability of water is very close to that of air, the inductance of the cable should not change noticeably.

To determine the magnitudes of these effects, test measurements similar to those made at TMI were made on the 10-ft standard samples of TMI cables. The cable parameters measured for various conditions were compared with the parameters of the same cable measured dry. Except for the dissipation factor, only the percent change in the cable parameters were considered. The absolute magnitude values were not used to replace control cable measurements made at TMI because the accuracy obtained with a 10-ft section of cable should be less than 60-ft sections measured at TMI. On multiconductor cables with more than three conductors, the distance between the conductors varied. The two extremes were adjacent and opposite conductors, where opposite means two conductors on opposite sides of a cable diameter. Figure 1 shows the various cable configurations with an indication of the conductor between which the measurements were made. For these cables, measurements were made on both adjacent and opposite conductors. Note that only a single set of measurements were taken for each configuration. Improved statistical measurement accuracy could have been obtained if a larger number of cables had been available for testing.

Table 1 summarizes the test data for cable tray and conduit tests. Data were taken with dry cables on a cable tray, in a dry conduit, and in a water filled conduit (the cable ends were kept out of the water so that the interior of the cables were kept dry). The table shows the results as the percent change from a dry cable on a nonmetallic surface for each parameter except for dissipation factor for which the actual values at 1 kHz are given. For comparison, data are also included for the cables injected with water similar to that in the actual cables at TMI. The simulated solution contains 1,000 ppm Na+ and 3800 ppm of boron with a conductivity of 1.32 ms. Most of the effects due to the cable tray and conduit were small; however, the capacitance of the FR-9HH cable increased noticeably in the wet (water filled) conduit. This should be due to the electric field outside the cable being affected by the water dielectric. The characteristic impedance of the FR-9HH opposite conductors increased 11.7% when laying in the cable tray. This is not consistent with the capacitance and inductance changes for the same test, but has not been explained.

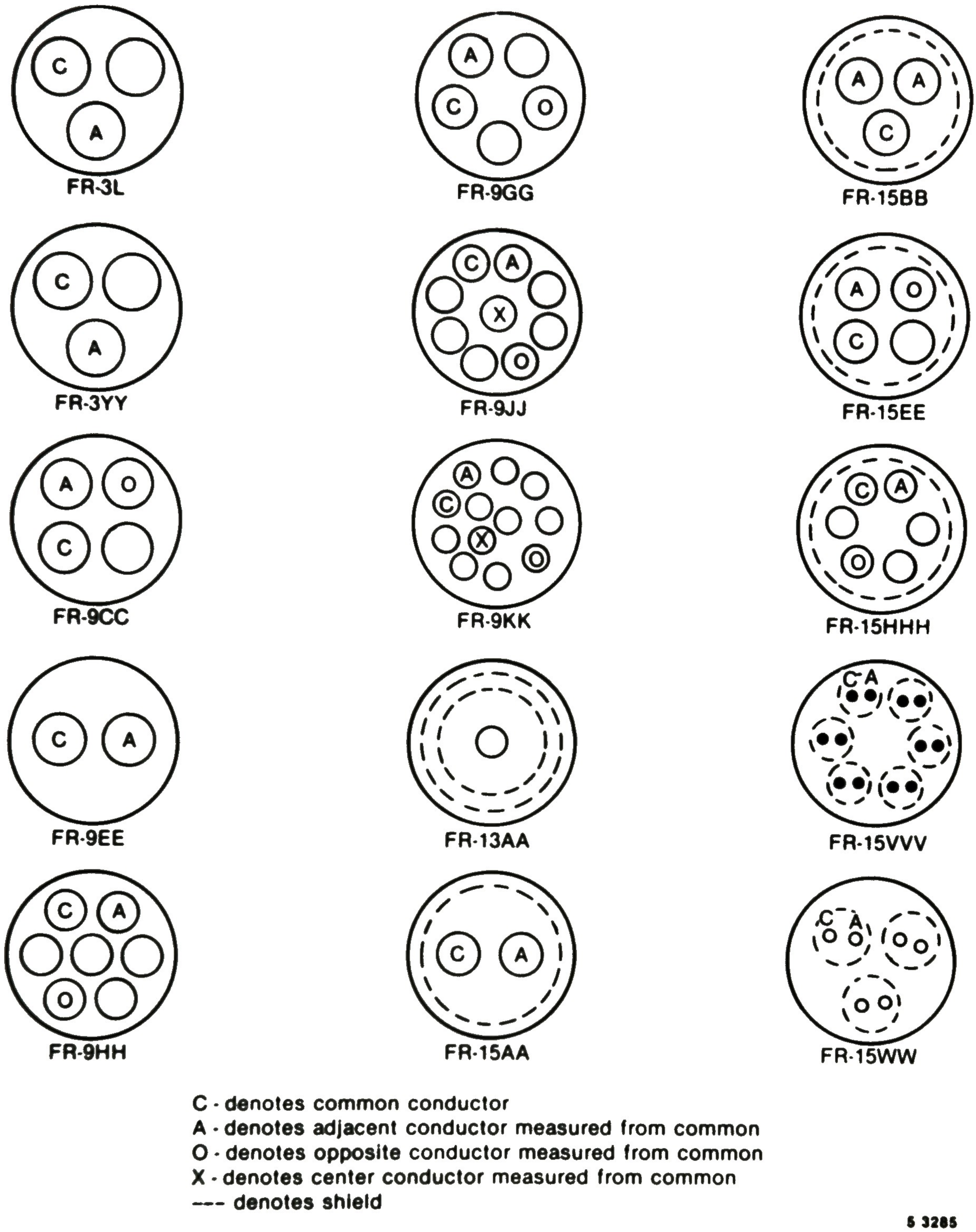


Figure 1. Conductor configuration for the various types of cable tested.

TABLE 1. SUMMARY OF CONTROL CABLE TEST RESULTS

Cable ID	Conductors[b]	Cable Wet	Cable In Dry Tray	Cable In Dry Conduit	Cable In Wet Conduit
Capacitance[a]					
FR-3YY	3/C #12	79.3	-2.4	-1.6	2.1
FR-9HH	7/C #12 ADJ	43.1	1.3	1.7	14.5
FR-9HH	7/C #12 OPP	145.5	3.6	5.9	31.0
Velocity of Propagation[a]					
FR-3YY	3/C #12	-10.5	0.0	0.5	-5.3
FR-9HH	7/C #12 ADJ	-3.9	0.7	0.0	-2.5
FR-9HH	7/C #12 OPP	-4.4	1.0	0.7	-4.2
Characteristic Impedance[a]					
FR-3YY	3/C #12	-8.8	2.7	1.0	-2.4
FR-9HH	7/C #12 ADJ	-6.1	4.2	6.0	1.4
FR-9HH	7/C #12 OPP	-4.0	11.7	8.9	5.4
Inductance[a]					
FR-3YY	3/C #12	-4.3	-2.4	-3.5	-3.1
FR-9HH	7/C #12 ADJ	2.9	2.5	1.7	1.7
FR-9HH	7/C #12 OPP	1.6	1.6	1.0	1.0
Dissipation Factor					
		wet/dry			
FR-3YY	3/C #12	.12/.11	0.11	0.11	0.11
FR-9HH	7/C #12 ADJ	.017/.018	0.015	0.018	0.019
FR-9HH	7/C #12 OPP	.020/.019	0.018	0.017	0.020

a. Except for dissipation factor, values shown indicate percent change relative to dry cable on a nonmetallic surface.

b. 3/C #12 means three-conductor #12 AWG cable.

Influences external to the cables, such as conduits, have the largest effects on cable parameters when the conductors of a pair being tested are farthest apart. This is expected because the fields of two conductors close together are more confined and less influenced by external factors than two more widely spaced conductors.

Wet Cable Tests

Table 2 lists the percent changes observed when comparing the measurements on dry cable with the measurements made on cables injected with the simulated TMI solution.

Because the TMI solution had a dielectric constant almost equal to water and a permeability of 1.0, it was expected that the cable capacitance would increase according to the amount of void filled by the solution and that inductance would not change. The characteristic impedance (Z_o) and velocity of propagation (v_p) are both inversely proportional to the square root of the dielectric constant, and therefore were both expected to change by the inverse of the square root of the capacitance ratio. The dissipation factor was expected to increase because of added conductance and dielectric losses.

Table 2 shows that Z_o and v_p decreased as expected. The amount they decreased was approximately equal, also as expected. The capacitance increased as expected, but by a much larger amount (in most cases) than would be indicated by the Z_o and v_p changes. The larger-than-expected increase in capacitance has not been explained. Because only 10-ft samples of each cable type was available for measurements, the capacitance value was small (about 200 picofarads, dry), which made the measurements more susceptible to errors owning to stray capacitance. The inductance values were also small, and all indicated inductance percentage changes were small and thought to have been caused by resultant measurement errors.

The dissipation factors are not given as percentage changes because they are independent of length, and because the values for some of the dry

TABLE 2. CHANGE IN CONTROL CABLE TEST RESULTS (dry versus wet)

Cable ID	Comments	Cap[c]	Dissipation Factor Dry/Wet	Induct[c]	Z_o[c]	v_p[c]
FR-3L	3/C #10	2.1	0.012/0.014	1.35	-1.7	0.0
FR-3YY	3/C #12	79.3	0.12/0.11	-4.31	-8.8	- 7.9
FR-9CC	4/C #9 ADJ	37.5	0.071/0.050	0.91	-17.8	-18.2
FR-9CC	4/C #9 OPP	111.5	0.084/0.26	1.89	-21.2	-21.2
FR-9EE	2/C #12	85.1	0.012/0.19	2.54	-19.1	-10.5
FR-9GG	5/C #12 ADJ	71.5	0.013/0.014	-0.45	-9.5[b]	-10.1
FR-9GG	5/C #12 OPP	123.8	0.010/0.013	-0.35	-11.0[b]	-10.5
FR-9HH	7/C #12 ADJ	43.1	0.017/0.018	2.90	-6.1	-3.9
FR-9HH	7/C #12 OPP	145.5	0.020/0.019	1.61	-4.0	-4.4
FR-9JJ	9/C #12 ADJ	96.9	0.046/0.18	3.43	-12.2	-10.8
FR-9JJ	9/C #12 OPP	187.4	0.056/0.21	1.13	-12.9	-12.8
FR-9JJ	9/C #12 CNTR	136.5	0.057/0.24	1.89	-9.4	-8.5
FR-9KK	12/C #12 ADJ	101.1	0.066/0.042	2.00	-14.9	-14.1
FR-9KK	12/C #12 OPP	153.0	0.099/0.028	0.26	-9.6	-11.9
FR-9KK	12/C #12 CNTR	89.7	0.077/0.033	1.02	-8.7	-8.6
FR-13AA	1/C #16 TRIAX	1.0	0.003/3.16	-11.04	-0.4	-3.7
FR-15AA	2/C #16 S	126.6	(a)/0.021	1.90	-7.3	-5.1
FR-15BB	3/C #16 S B&W	13.9	0.00/(a)	-0.85	-2.4	-4.1
FR-15BB	3/C #16 S B&R	72.9	(a)/0.31	0.00	-2.2	-6.9
FR-15EE	4/C #14 S ADJ	20.6	(a)/0.001	0.00	-7.7	-5.7
FR-15EE	4/C #14 S OPP	29.3	(a)/(a)	1.11	-5.7	-7.5
FR-15HHH	6/C #16 S ADJ	44.3	0.008/0.001	0.00	-16.4	-11.9
FR-15HHH	6/C #16 S OPP	65.3	0.006/NA	0.00	-22.5	-12.9
FR-15VVV	12/C #16 3-PR/S	11.8	(a)/0.005	0.40	-8.8	-2.8
FR-15WW	6/C #16 3-PR/S	-0.8	0.001/(a)	-0.43	+2.0	0.0

ADJ - Adjacent conductors measured.
OPP - Opposite or nearly opposite conductors measured.
CNTR - Measurement made between an outer and center conductor.
B&W,B&R - Measurements between black and white or black and red conductors.
S - Denotes shielded cables.
3-PR/S - Denotes twisted shielded pair cable.

a. Too small to measure.

b. TDR slope changed from positive to negative.

c. Values shown indicate percent change except for dissipation factors, which are actual values at 1 kHz.

cables are so small that they could not be reliably measured. For this analysis, the actual dissipation factors rather than their ratio are more informative. Only a few cables had significant increases in dissipation factors.

Additional measurements of this type on much longer cables and several samples of each type of cable are needed if consistent and accurate results are to be obtained.

TDR Measurements of a Wet Terminal Block with Cable

In addition to measurements made on the cables, others were made on terminal blocks to determine the effects of water on connections. A number of TDR measurements (see Appendix B) were made on a terminal block at the end of a 28.5-ft section of FR-3YY cable. With the terminal block dry, the cable was effectively terminated in an open circuit. This was the reference case, and produced the TDR display shown in Figure 2. The open circuit at the end of the cable is seen at about two thirds of the way across the display. The maximum level of the TDR display is greater than +1 because of reflections. After they have decayed the level is +1. Figure 3 shows the results when a simulated TMI solution was poured on the terminal block and allowed to run off. No effects were noticed. In Figure 4, the TMI solution was allowed to accumulate until the terminal block was partially submerged in the solution. Notice that the highest level of the TDR display has been noticeably reduced. This means that the solution is allowing conduction across the terminal block and looks like a resistive termination. In Figure 5, the terminal block is totally submerged in the solution. Two effects were noted. First, the conduction increased until the effective termination resistance was almost equal to the cable impedance. It is computed from the TDR data as 119 ohms. Second, a small dip at the end of the cable indicates a small capacitance. Figure 6 shows a TDR display of the cable terminated by a resistance that was adjusted to give about the same level as was seen in Figure 5. The resistance was measured as 122 ohms. Notice that the capacitive dip at the end of the cable is not present with only a resistive termination.

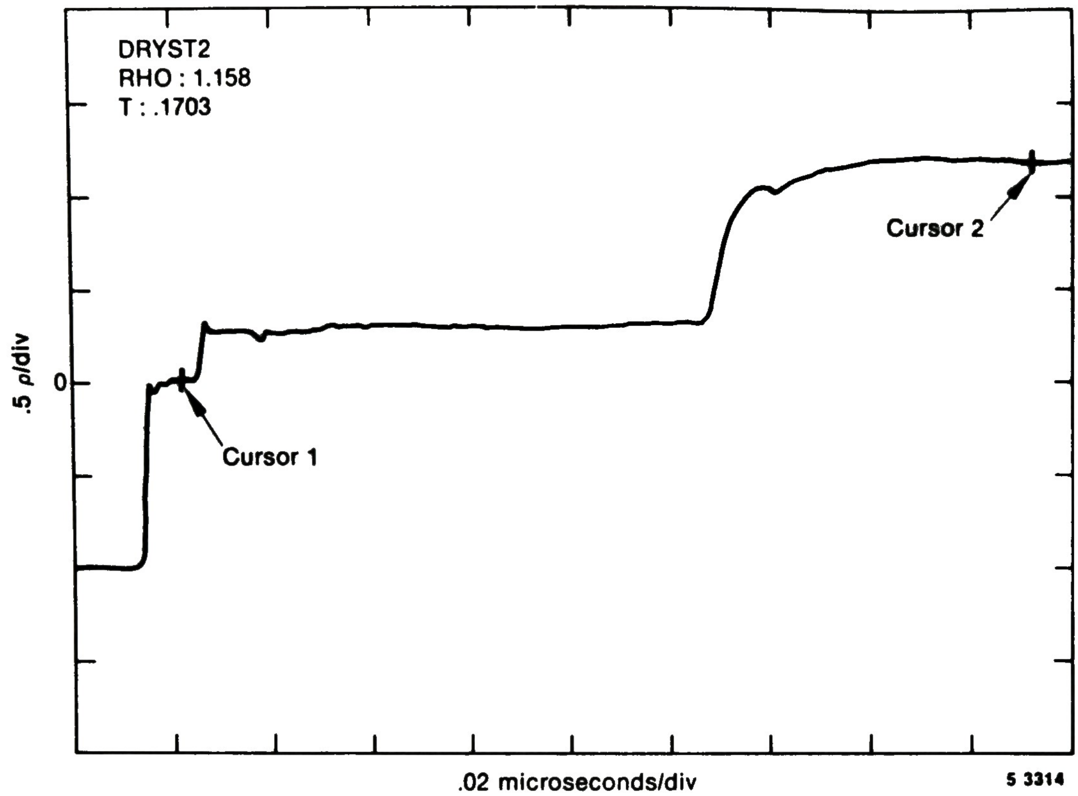


Figure 2. TDR display of a cable terminated with a dry terminal block.

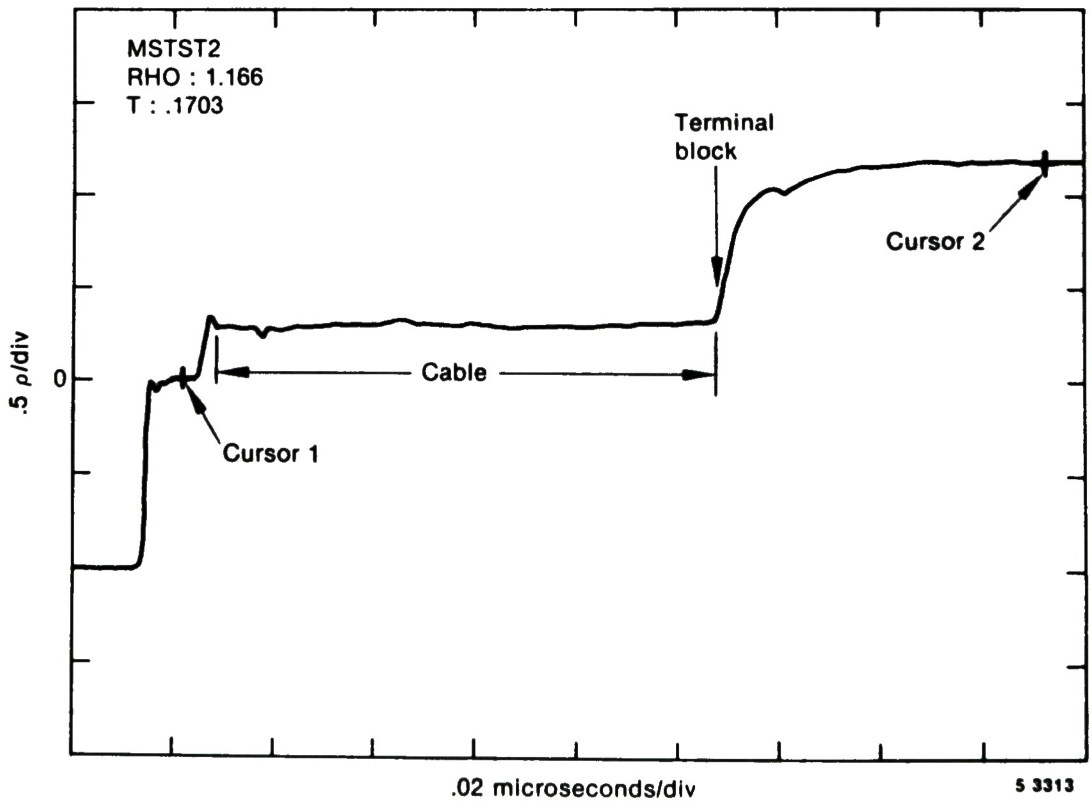


Figure 3. TDR display of a cable terminated with a terminal block wetted with a TMI solution.

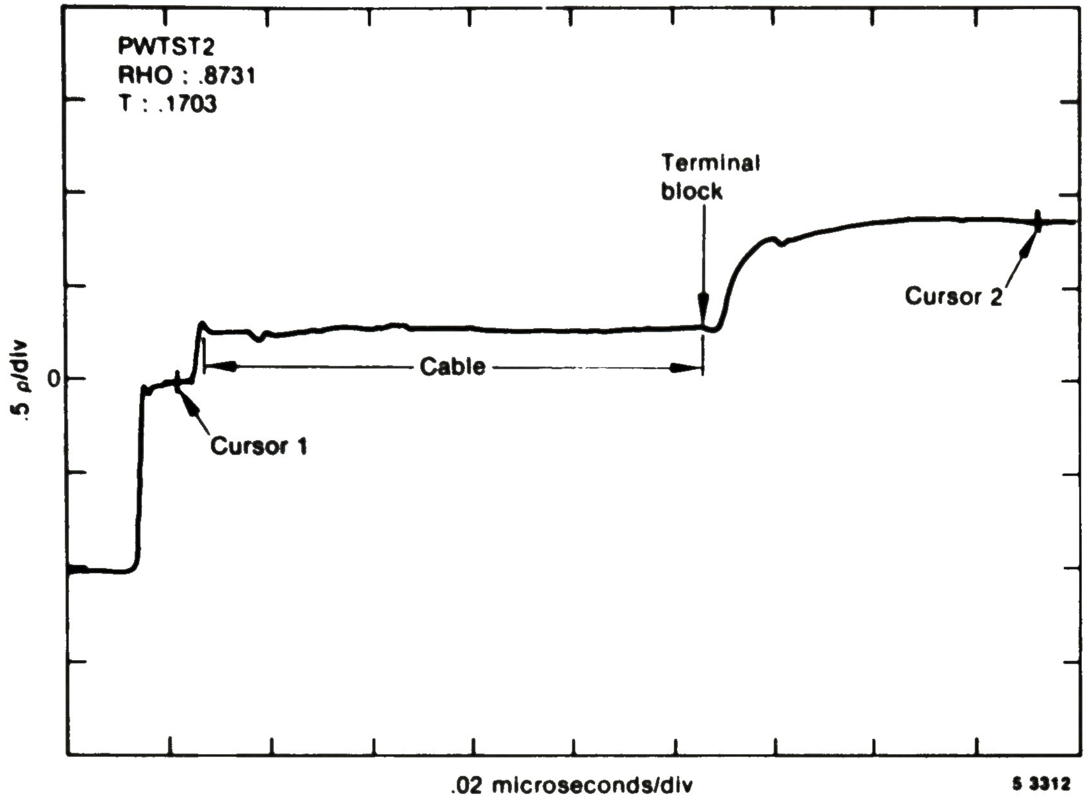


Figure 4. TDR display of a cable terminated with a terminal block partially submerged in a TMI solution.

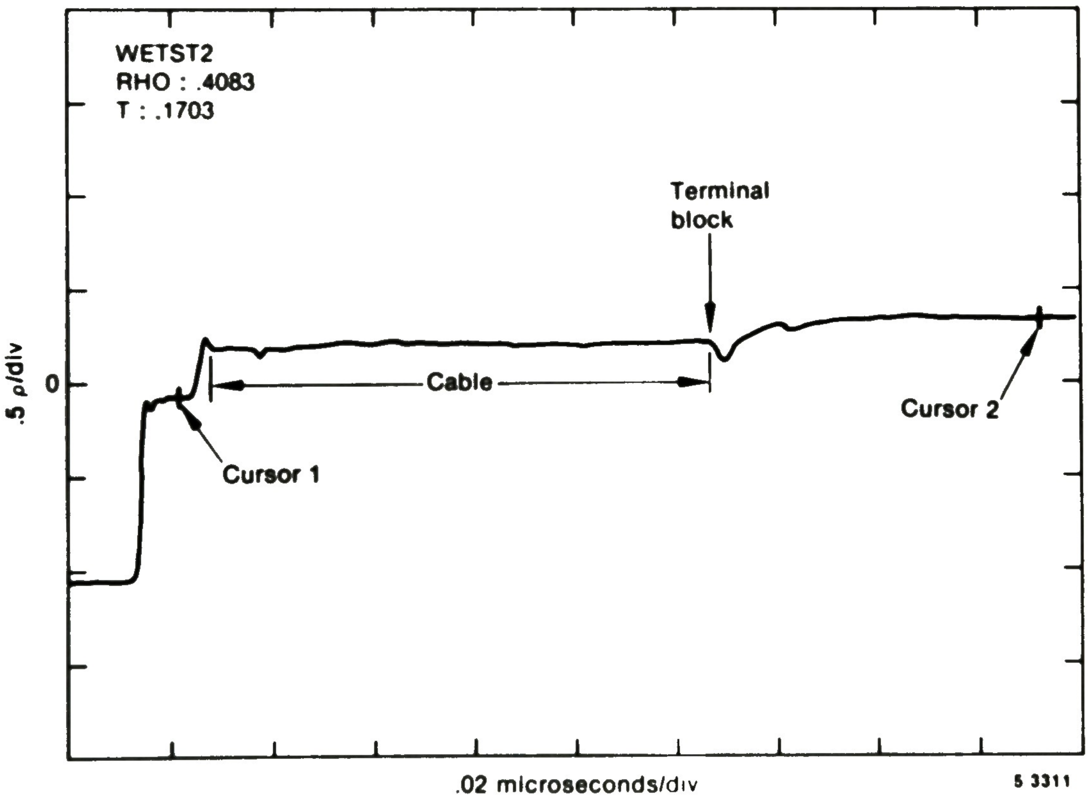


Figure 5. TDR display of a cable terminated with a terminal block totally submerged in a TMI solution.

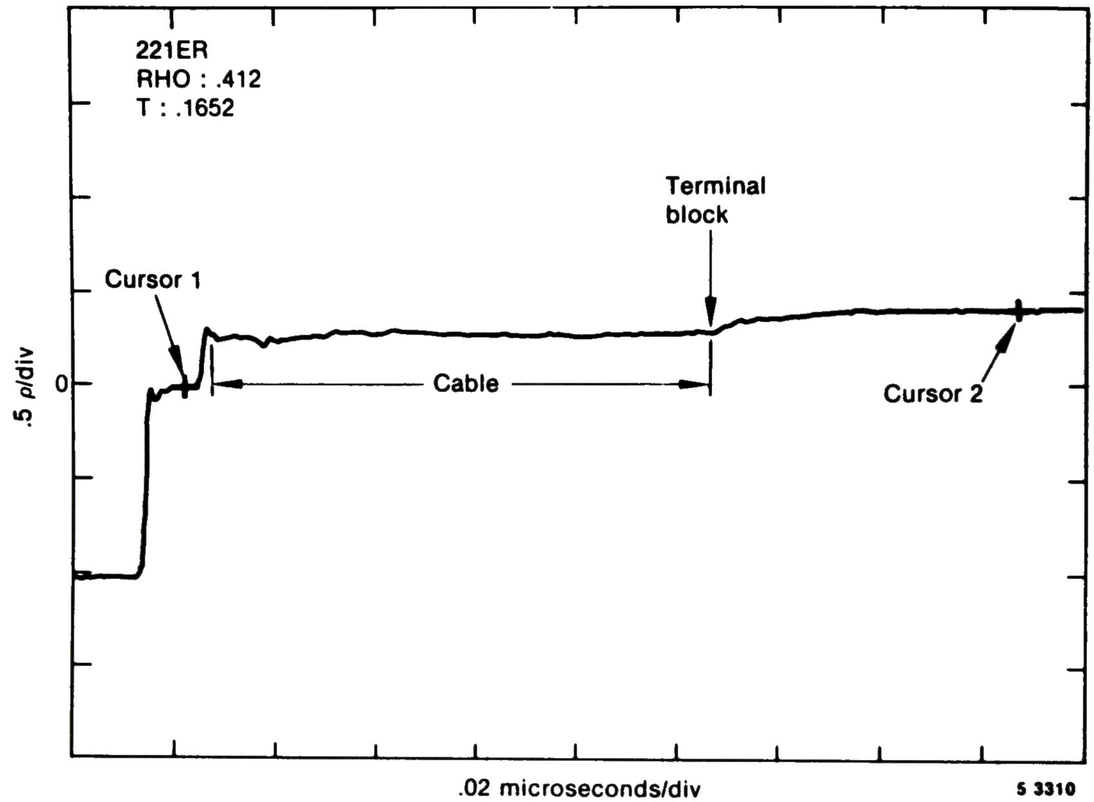


Figure 6. TDR display of a cable terminated with a 122 ohm load.

Figure 7 is a repeat of Figure 5, with a larger time scale. Figure 8 shows the TDR display when the TMI solution (see Figure 7) is replaced with tap water. Comparing Figures 7 and 8, it can be seen that the conductivity of tap water was less than the conductivity of the TMI solution. It had an effective resistance of 879 ohms. The capacitive dip was also a little smaller.

Conductance and Capacitance Measurements of a Wet Terminal Block

The conductivity of the wet terminal block (without a cable) was measured with a FLUKE Model 8050A digital multimeter. With the terminal block submerged in tap water, a small open circuit voltage of -2.2 mV, probably caused by electro-chemical action, was measured before measuring the resistance. When the ohmmeter was first applied, the resistance was about 3k ohms and rapidly increasing. After 18 minutes the reading was about 7.2k ohms and fluctuating. Switching to the 200k ohm scale gave about the same reading. The meter was switched from ohms to current to discharge the system being measured. After the current had decayed, the leads were reversed and the meter switched to ohms. Readings were approximately the same as before reversing the leads.

The measurements were repeated using the TMI solution in place of tap water. The open circuit voltage was about 0.016 volts. The meter was switched to ohms and indicated about 2.2k ohms at the start. After 15 minutes, the reading was about 4.33k ohms on the 20k-ohm scale and about 2.5k ohms on the 200k-ohm scale. As with tap water, in addition to drift there were fluctuations large enough to occasionally reverse the direction of change in resistance readings. The leads were reversed and the indicated[a] resistance started at about -2.4k ohms and drifted to

a. Indicated negative resistance is caused by a voltage source within the circuit being measured. In this case, the voltage was 0.016 volts. Reversing the meter leads will give a positive reading. Neither reading is correct. Some meters disable the display sign (+/-) in the resistance mode and only display the magnitude of the result. The Hewlett-Packard 3456A

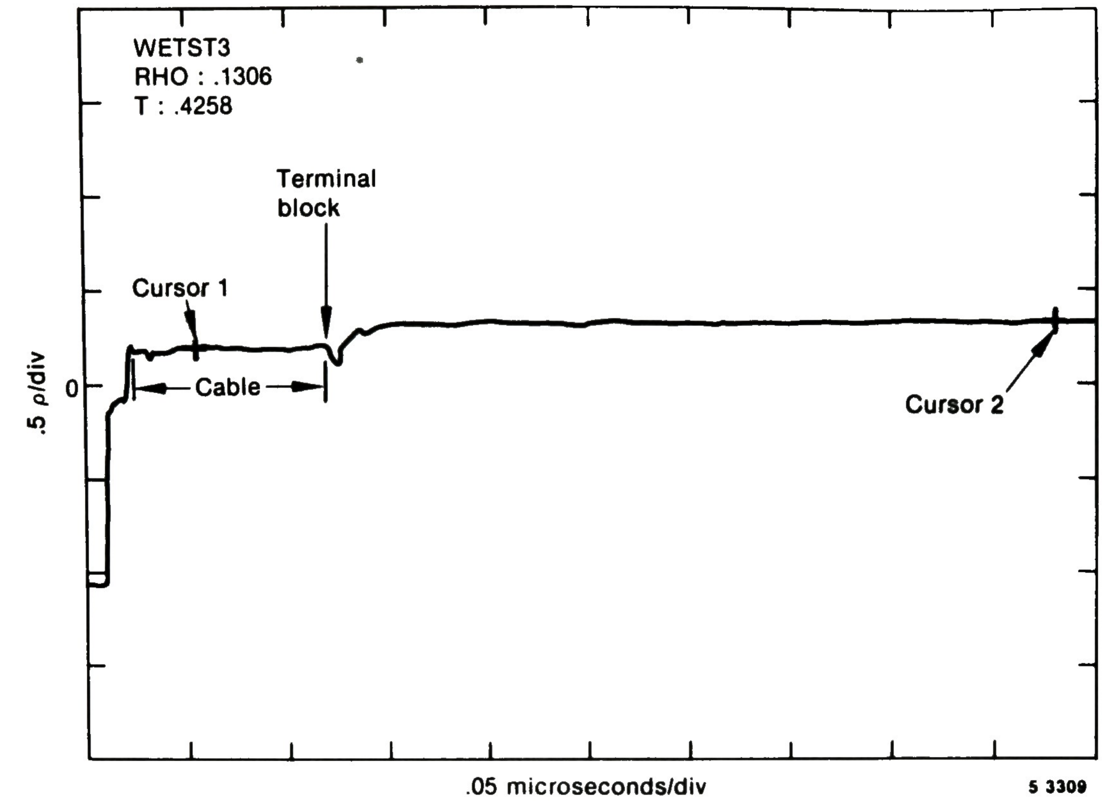


Figure 7. TDR display of a cable terminated with a terminal block totally submerged in a TMI solution.

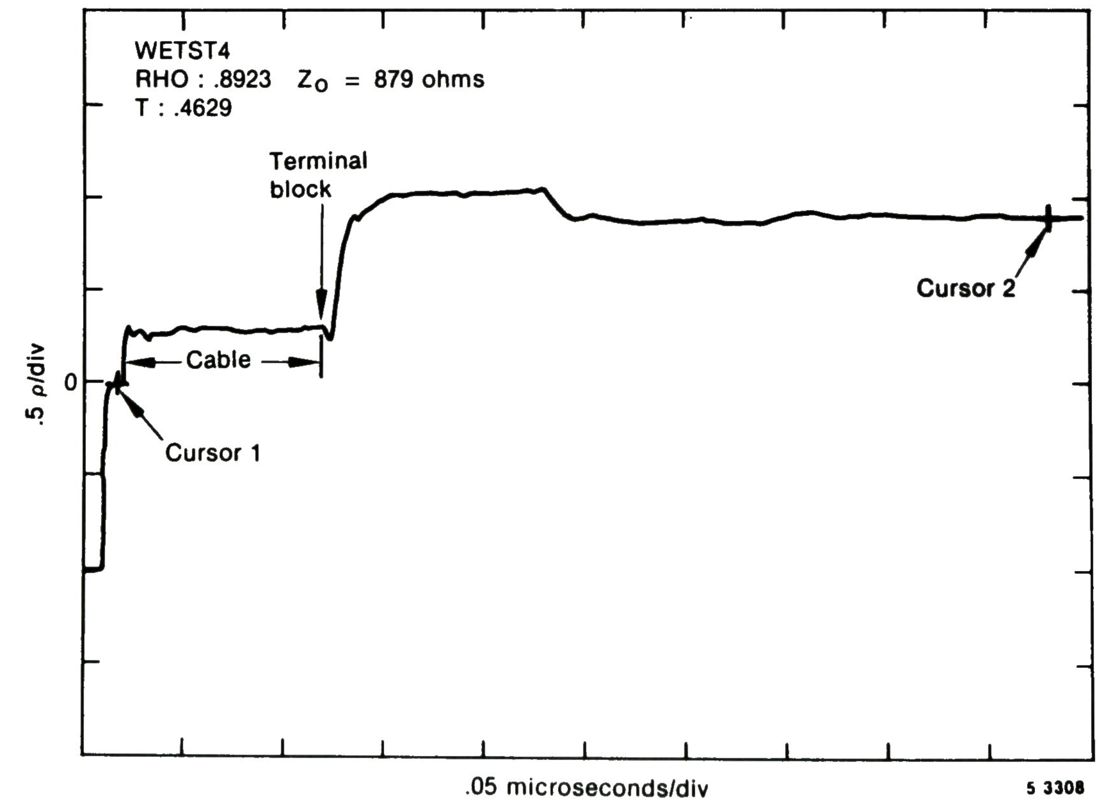


Figure 8. TDR display of a cable terminated with a terminal block totally submerged in tap water.

-1.11k ohms in 8 minutes on the 20k-ohm scale. Switching to the 2k-ohm scale at this point gave a positive resistance reading. The solution was poured out, the terminal block rinsed, and the solution replaced. After sitting for 30 minutes, the open circuit read 0.045 volts, and a quick resistance reading gave about 4.4k ohms on the 20k-ohm scale. A quick reading with the leads reversed gave -2.4k ohms. At this point, a currentreading on the 2-mA scale decayed to about 0.025 mA. Then, a quick resistance reading with leads reversed gave about -2k ohms.

In summary, one possible cause for abnormal resistance values is a wet connection that results in electro-chemical action. The readings depend on meter circuitry, scale used, polarity of the leads, types of metals at the wet connection, type and concentration of the solution, and possibly other factors. Note, however, that a changing dc resistance reading on an open-circuit cable system can be a reliable method of detecting the presence of moisture.

Because the dc resistance measurements were not well defined, ac conductance (reciprocal of ac resistance) was measured along with capacitance, using a HP4192A LCR meter. These measurements were more stable than the dc measurements, though some settling time was needed before readings were taken at low frequencies. These measurements were made with both short leads and a 28.5-ft cable.

The conductance and capacitance data obtained from the LCR meter were for an equivalent circuit of a capacitor in parallel with the conductance. If the conductance and capacitance vary with frequency, it is possible that the circuit is more complex than a single conductance and capacitor. This will be discussed further after some results are shown. Measurements were taken over the frequency range of 5 Hz to 100 kHz for three different test

---

systems DVM has an offset compensated mode that will correct for the circuit voltage (offset voltage) caused by thermal effects. This compensation should improve measurement results for circuits with electro-chemically generated offset voltages, but errors caused by charging of the offset voltage source by the ohmmeter currents will remain. Further investigation of these effects are needed for a detailed understanding of the effects of wet connections.

voltages. This frequency range was much wider than the TMI measurement frequency range in order to give as much insight as possible into phenomena observed. Results for the terminal block submerged in tap water are shown in Figures 9 and 10. Figure 9 shows that the conductance varied both with frequency and amplitude of the test voltage. These variations have not been explained but should be noted for comparison with in situ test data. The dc resistance cannot be inferred from the data except that it is probably much larger than the value at 5 Hz. The in situ data were not presented in the form of ac conductance but were given as dissipation factor. Figure 10 shows the equivalent capacitance measured for the terminal block in tap water. It indicates that the test voltage has no significant effect on the capacitance. Figure 10 also indicates two unexpected phenomena. First, the equivalent capacitance is extremely large compared to that expected from the configuration and dielectric materials. A constant 10^{-10} F would seem more likely. Second, there is an extreme variation of capacitance with frequency. The resulting frequency variations in capacitance and conductance for a terminal block submerged in water can be approximately modeled by the equivalent circuit shown in Figure 11. Here C_1 is probably due to the dielectric effects around the Terminal block, G_1 due to conduction between the terminals, and G_2 and C_2 because of the electro-chemical effects. The equivalent circuit in Figure 11 gives a response similar to that in Figure 10.

The terminal block was also submerged in the TMI solution and the above measurements were repeated. Finally, the terminal block was attached to the end of a 28.5-ft length of FR-3YY cable, and submerged again. A voltage of 1-volt was used for these tests. Figure 12 shows the conductance data for three situations. The TMI solution had a much higher conductance, as expected, because of the higher concentration of free ions. With the TMI solution, the 28.5-ft cable had higher conductance than the short leads because the size and length of the exposed conductors was larger and some drift in readings were caused by the longer settling time. At higher frequencies, the dielectric losses of the cable add extra equivalent conductance.

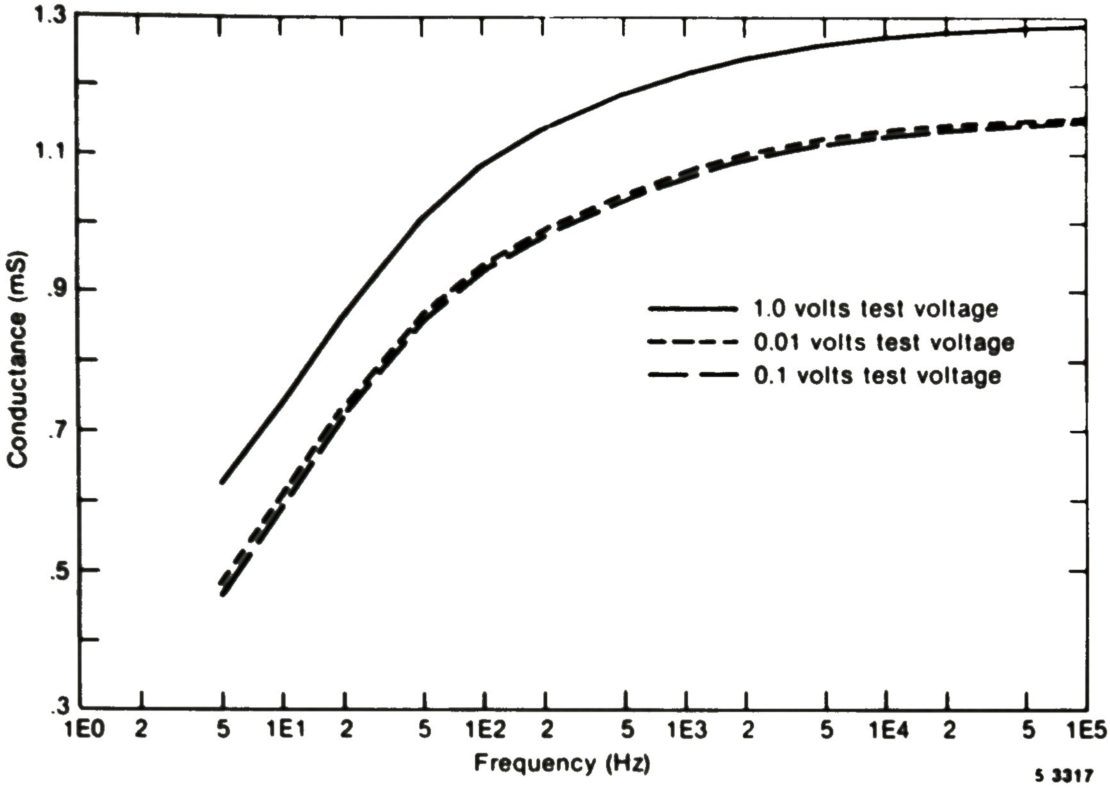


Figure 9. Conductance of a terminal block submerged in tap water as a function of frequency and test voltage.

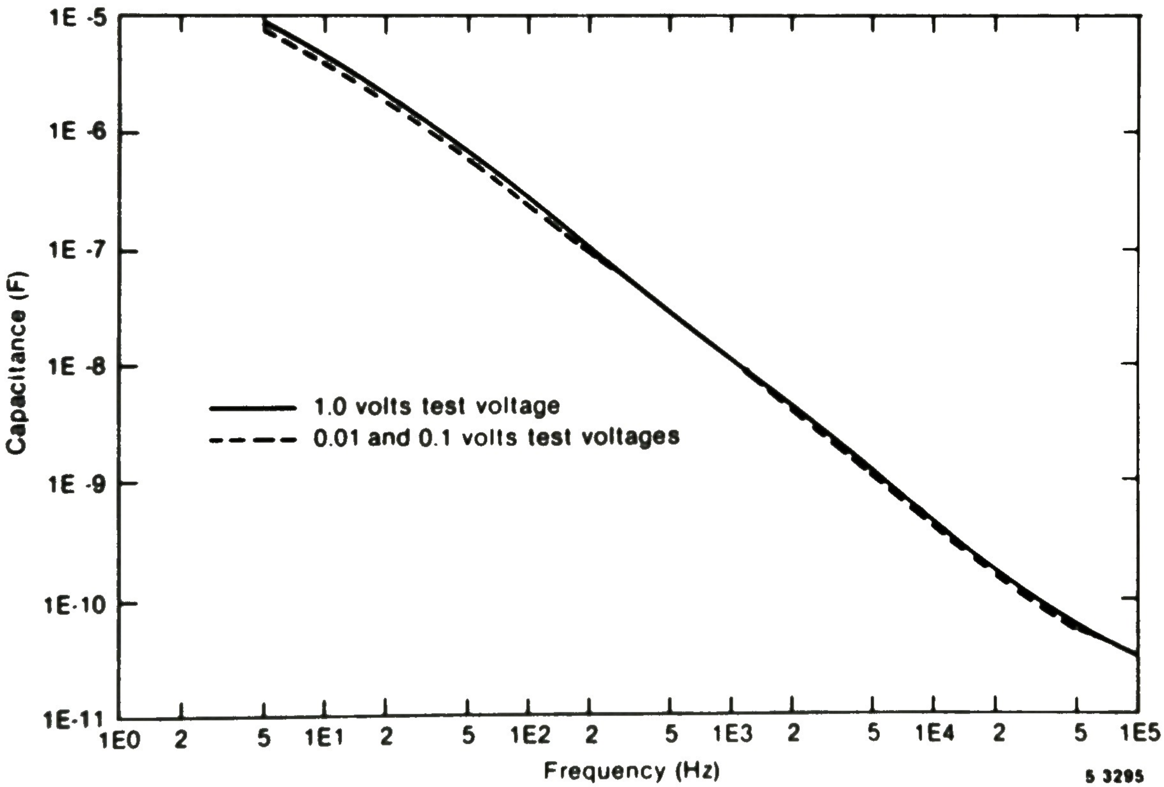


Figure 10. Capacitance of a terminal block submerged in tap water as a function of frequency and test voltage.

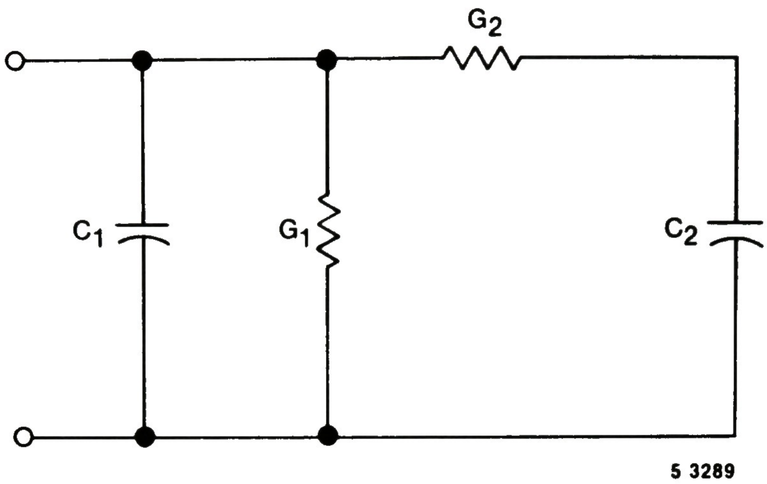


Figure 11. Equivalent circuit for approximating the conductance and capacitance of a terminal block submerged in water.

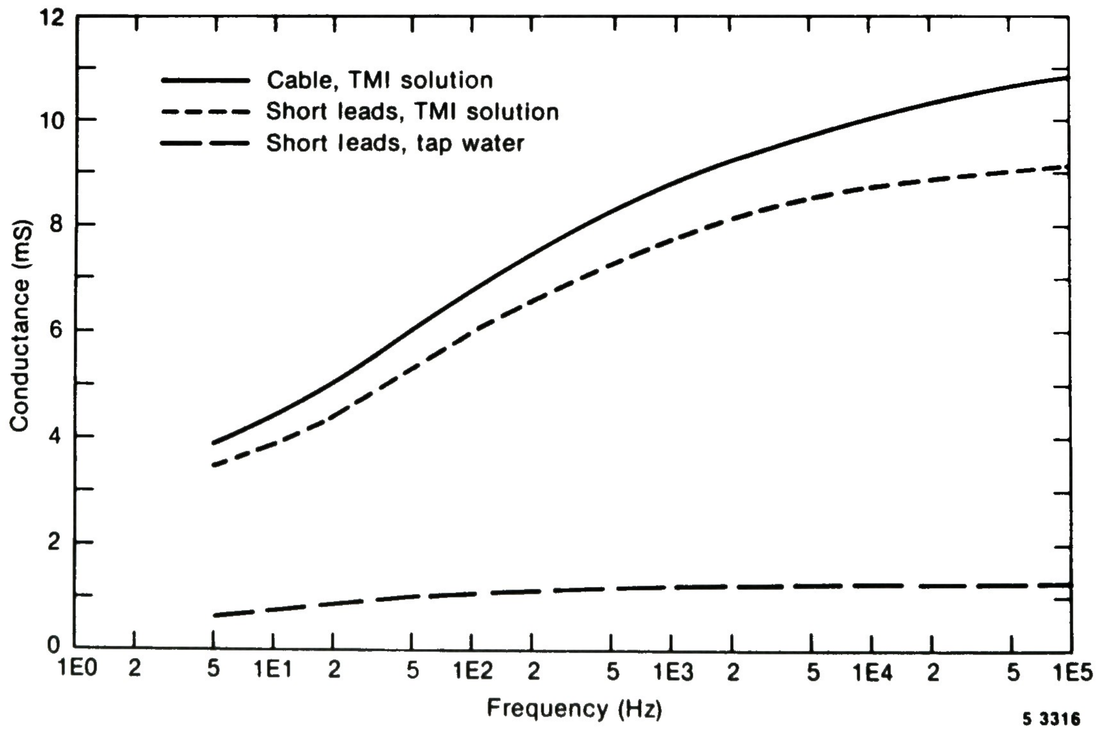


Figure 12. Conductance of a terminal block as a function of frequency for the various conditions noted.

Figure 13 presents capacitance data. Capacitance with the TMI solution is about six times larger than with tap water. The decrease in capacitance as frequency increases is probably caused by the electro-chemical effect as discussed above and modeled in Figure 11. This electro-chemical effect makes the capacitance appear abnormally high at low frequencies. The divergence of the curves at higher frequencies was probably caused by transmission line effects, and would be more pronounced for longer cables. Note that the capacitance with the TMI solution is about 0.2×10^{-6} F at 1 kHz where most of the in situ measurements were made.

Because the capacitance of the wet terminal block has a very high value at low frequencies and is increasing at these frequencies while all normal circuits at TMI have lower and constant capacitance values at these frequencies, capacitance measurements at several low frequencies might be used to confirm cases of suspected wet connections (other connections should have characteristics similar to terminal blocks).

The dissipation factor is probably a more useful parameter because it is the ratio of dissipated energy to stored energy and is in a sense normalized to be independent of physical size. Using the conductance and capacitance values from laboratory data, the dissipation factor was computed for three different test conditions and is plotted in Figure 14. Note that the dissipation factor is high and increases with increasing frequency. Note that the dissipation factor obtained using tap water is several times higher than the dissipation factor obtained using the TMI solution.

Summary of Laboratory Measurements

Laboratory measurements indicate that wet cables had higher capacitance, lower characteristic impedance, lower velocity of propagation, and higher dissipation factors than dry cables. These results were as expected from theoretical analysis. The amount of change varied for different cable types, from negligible for all parameters for some cables,

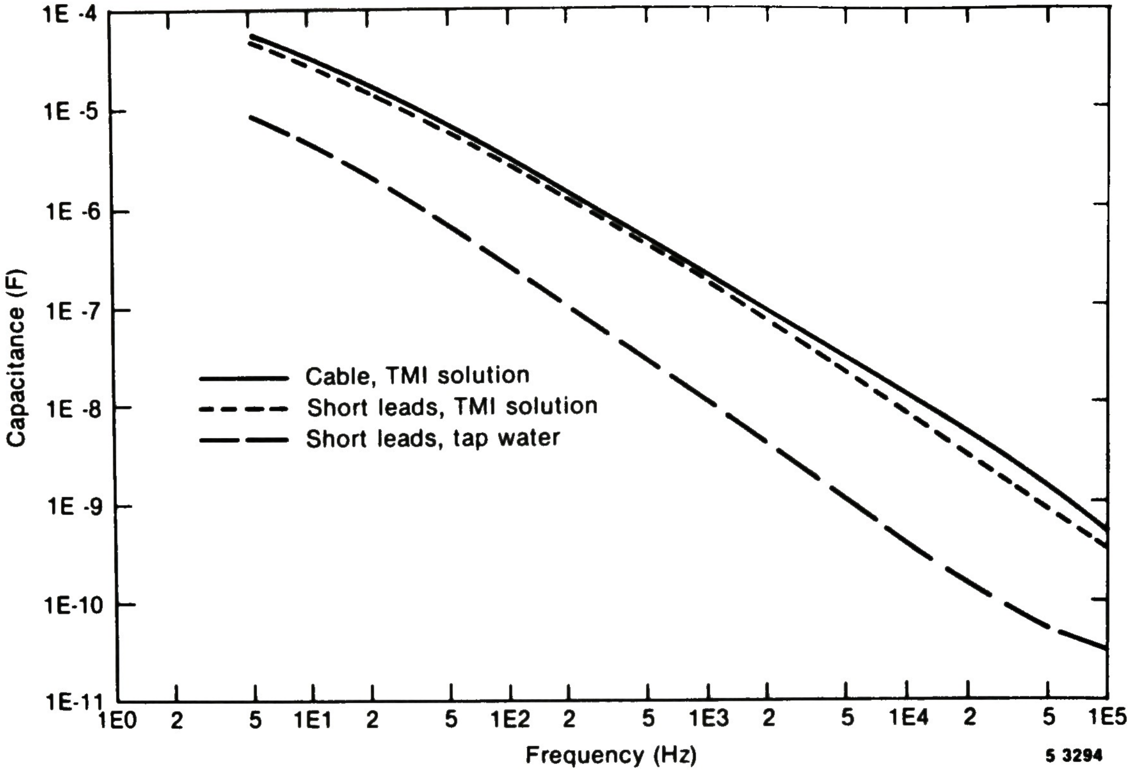


Figure 13. Capacitance of a terminal block as a function of frequency for the various conditions noted.

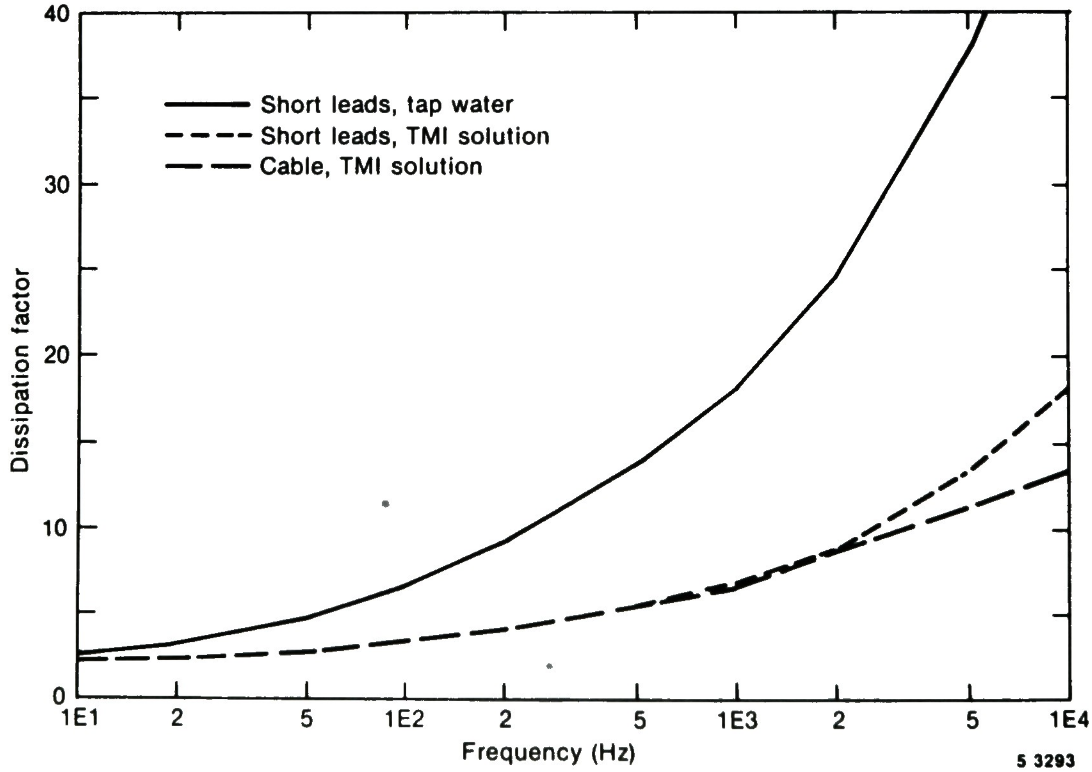


Figure 14. Dissipation factor of a terminal block as a function of frequency for the various conditions noted.

to +187% capacitance change, -22.5% characteristic impedance change, and -21.2% velocity of propagation change for the worst cases of other cables. The percent of change was larger for conductors separated farthest in a cable. This was because a void was more likely between conductors widely separated. The change in inductance caused by water in the cable was practically zero since the permeability of water is the same as the cable voids. The measured changes were small and can be attributed to measurement errors.

Unshielded cables lying on a dry cable tray or conduit had small parameter changes. Changes in capacitance, velocity of propagation, and inductance were negligible for the cable tray, and the characteristic impedance measured almost 12% high for one cable. Similar results were obtained for the dry conduit, but water-filled conduit (but no water inside the cable) had larger capacitance changes due to the high dielectric constant of the water. The dissipation factor did not seem to be affected by these conditions.

When the terminal block at the end of a cable was partially submerged in water, it did not show significant change on the TDR display. Total immersion caused the terminal block to appear to have a resistance of about 122 ohms for a simulated TMI solution (chemically similar to water in containment). Tap water appeared to have a resistance of about 880 ohms; the difference was probably caused by lower conductivity. The wet terminal block showed a small capacitive component on the TDR, but when measured with an LCR meter at low frequencies gave much different results.

At low frequencies, a submerged terminal block appeared to have a very large capacitance, about 10^{-5}F at 5 Hz for the TMI solution. This is thought to be caused by electro-chemical action. The same effect caused dc resistance measurement problems. Voltage was generated at the terminal block, causing certain ohmmeters to give negative resistance readings. The effect should be investigated further to see if an offset compensated resistance meter, such as the HP3456A, reads correctly and if the effect can be used to identify wet terminal blocks.

ANOMALIES

The in situ data were evaluated to understand the condition of the cables and other reactor building components by looking for deviations (anomalies) from values expected for good circuits. Since a baseline of preaccident measurement data was not available for the circuits of interest, an estimate of expected values used for the analysis was obtained from measurements made on "control" cables and from data on the other components. Most of the control cables were 60-ft lengths of each type of cable. Measurements on these cables were made with the same instruments used for the in situ measurements. The expected values for each circuit were calculated from the cable data and from the best data available for the other circuit components. For some circuits, the expected values were obtained by using statistical methods on the actual in situ data. The in situ data recorded are described in the following paragraphs.

- dc loop resistance Loop resistance is composed of three parts that are not separately measurable: resistances of the penetration, the cable, and the connectors and termination. When the termination was a switch or relay contact, the loop resistance was expected to be equal to the cable resistance, within measurement accuracy. A lower than expected value of loop resistance for this type of circuit can be explained as a less than expected per unit resistance for the cable, a shorter than expected cable length, or a very low resistance path between leads in the cable. The TDR data could be used to define the cause of low loop resistance. No problems such as these were observed in the data.

  For circuits with switches and relays, the predicted values were made for two cases. When the switch or relay contacts were open, the predicted value was "open," i.e., over range on an ohmmeter. When the switch or relay contacts were closed, the contact resistance was negligible compared to the resistance of cable conductors, therefore the loop resistance was calculated as the documented length multiplied by the resistance per foot measured on a control cable of the same type. The documented length was the amount of cable shown issued for these cables during construction. When the terminating device resistance was not negligible, it was added to the cable resistance to get the loop resistance. In some cases when the terminating resistance value was not known and a large number of the same type circuits were measured, statistical methods were used, i.e., the circuits were compared to each other. The estimated value of the cable resistance was subtracted from the measured loop resistance for each measurement, leaving a value attributed to the terminating device. These values were then averaged and used as the expected value of the terminating device resistance. Circuits with active terminations, such as transmitters, loose parts monitors, neutron detectors, etc., did not have an accurately predictable value of dc resistance, therefore no expected values were calculated for them.

- Capacitance Methods similar to those used for loop resistance were used for capacitance measurements. One important difference between the capacitance and loop resistance measurements was that there were cases when no capacitance measurement was available. These occurred when the reactive part of the impedance being measured was inductive. This usually happened when the cable termination impedance was relatively small or inductive, e.g., shorts, pressurizer heaters, motors, etc. Expected capacitance values for open-circuited cables were computed as the cable documented length multiplied by the capacitance per foot measured on a control cable of the same type.

- Inductance These calculations were analogous to the capacitance calculations.

- TDR data Three main types of information were considered when TDR data were used. First, the velocity of propagation was calculated from the time required for the signal to travel to the end of the cable, as determined by the TDR system operator, divided by the cable documented length. The expected value for this was found by measuring a control cable of the same type. Second, the characteristic impedance (Z_0) of the cable conductor pair was calculated from the TDR data. The expected value for Z_0 was calculated from the TDR data of the control cable. Third, the shape of the TDR data display could usually be interpreted to give the location of unexpected opens or shorts. Symptoms of wet sections of cables were sometimes recognizable. The TDR data also indicate whether the fault is series or parallel, or inductive, capacitive, or resistive in nature.

- Insulation resistance Insulation resistance measures the circuit leakage through several paths such as the cable insulation, terminal blocks, and end device insulation. Individual leakage paths could not be measured directly because only connections at the penetration were easily accessible. Also with the end device connected, it was not possible to directly measure the leakage between two conductors in most cases. The only practical measurements were from the conductors to the pair or cable shield for shielded cables and from the conductors to plant ground in other cases. The measurement from conductors to a shield gave a well defined path from the conductors to the shield. The measurement from the conductors to plant ground was not well defined because it only measured where the cable touched a grounded structure, plus the end device insulation to ground.

- ac Resistance Methods similar to those used for dc loop resistance were used for ac resistance. One important difference when comparing ac and dc resistance values is that the effective ac resistance was generally slightly higher because of the skin effect of certain cables.

- ac Impedance The ac impedance is a measure of the combination of the resistive and reactive parts of a circuit. It will generally follow the same pattern as ac resistance. The ac resistance, dc resistance, and ac impedance at resonance can also be used as a quality check of the data. For most circuits, all three values will be within 10% of each other.

- Initial Voltage The initial voltage reading serves two purposes. First it will alert the operator to any hazardous voltage existing on the lines. The reading will also indicate any small ac and dc voltage on the line for the interpretation of the data. Any dc voltage on the line could indicate electro-chemical effects at some point along the circuit that would be considered as anomalous. The dc voltage will also affect the other circuit measurements mentioned in this section.

Anomaly Types

About 12 types of anomalies can be described for the in situ test data; however, about half of these are not clearly identifiable because of variations in the normal cable data, which obscure the anomalies. The remaining anomalies, which are listed in Table 3, are more easily identifiable and usable. The types of anomalies are discussed below.

Low Insulation Resistance

Insulation resistance primarily indicates the condition of the portions of a circuit that are near a ground. For circuits with continuous grounds, such as shields, conduits, or cable trays, the overall condition of insulation can be assessed. In other cases, only the condition of certain components, such as terminal blocks and terminations, can be assessed.

Table 4 lists the circuits with insulation resistance values less than 10^6 ohms. Those values listed as $<10^6$ ohms were measured with a high

TABLE 3. TYPES OF ANOMALIES

Anomaly Type	Possible Cause
Open or near open loop resistance (order of 10^6 ohms)	Open conductor, bad connection, missing termination, or failed termination
Zero TDR length	Open at penetration
High loop resistance (more than two times expected value)	Corroded connection
Low insulation resistance (less than 10^6 ohms)	Wet insulation or conduction path on terminal block
Reduced Z_0 section of cable	Wet section of cable
High capacitance (in range of that caused by wet cable)	Wet cable
Very high capacitance	Wet connection

TABLE 4. CIRCUITS WITH LOW INSULATION RESISTANCE (LESS THAN 10^6 ohms)

Cable and Connection ID[a]	Cable Type	Insulation Resistance	Termination	Probable Cause[b]
IT1535I J5/B to G	FR-15WW	6×10^5	Transmitter	A
IT2433I J6/B to G	FR-15AA	6.7×10^5	Transmitter	A
IT2433I J6/C to G	FR-15AA	6.0×10^5	Transmitter	A
IT2437I J6/R to X	FR-15AA	5×10^5	Transmitter	A
IT2437I J6/Z to X	FR-15AA	8.5×10^5	Transmitter	A
IT2441I J6/k to j	FR-15AA	4.2×10^5	Transmitter	A
IT2441I J6/r to j	FR-15AA	3.1×10^5	Transmitter	A
IT2447I J8/D to H	FR-15AA	2.5×10^5	Transmitter	A
IT2451I J8/g to b	FR-15AA	1.5×10^4	Transmitter	A
IT3599I 2B to 2A	FR-13B	1.55×10^4	Amplifier	A
IT4119I J8/r to j	FR-15AA	3.7×10^5	Transmitter	A
IT4121I J8/M to U	FR-15AA	3.3×10^3	Transmitter	A
IT4125I J8/d to v	FR-15AA	1.4×10^5	Transmitter	A
MB200C TB3/30 to gnd	FR-9HH	27.7	Limit Switch	B
MB200C TB3/31-gnd	FR-9HH	8.5×10^5	Limit Switch	A
MB437C TB9/24-gnd	FR-9JJ	1.92×10^3	Limit Switch	A
MB437C TB9/34 to gnd	FR-9JJ	1.62×10^5	Limit Switch	A
MD68C TB4/33 to 34	FR-9JJ	2.96×10^4	Limit Switch	A
MS88P TB2/22 to gnd	FR-3YY	9.3×10^4	Motor	A
MS90C TB6/28 to gnd	FR-9HH	1.7×10^4	Limit Switch	A
SP148P TB3/4-5-6 to gnd	FR-3N	3.1×10^5	Heater	A
S078P TB7/1-2-3 to gnd	FR-3N	2×10^5	Heater	A
S080P TB7/4-5-6 to gnd	FR-3N	22.5	Heater	B
S084P TB9/1-2-3 to gnd	FR-3N	1.2×10^5	Heater	A
S0141P TB6/7-8-9 to gnd	FR-3N	5×10^4	Heater	A
S0168P TB8/1-2-3 to gnd	FR-3N	5×10^4	Heater	A
S0172P TB8/7-8-9 to gnd	FR-3N	5×10^4	Heater	A
S0176P TB10/4-5-6 to gnd	FR-3N	3.2×10^5	Heater	A
H291I J2/A to E	FR-15VV	$<10^6$	Flow Switch	A
H291I J2/A to shield	FR-15VV	$<10^6$	Flow Switch	A
H303I J3/B-C to G	FR-15VVV	$<10^6$	Level Switch	A
H303I J3/A to F	FR-15VVV	$<10^6$	Flow Switch	A
H315I J4/A-E to F	FR-15VVV	$<10^6$	Flow Switch	A
H315I J4/R-Z to X	FR-15VVV	$<10^6$	Level Switch	A
H317I J4/p-n to h	FR-15WW	$<10^6$	Level Switch	A
H317I J4/g-a to b	FR-15WW	$<10^6$	Level Switch	A

TABLE 4. (Continued)

Cable and Connection ID[a]	Cable Type	Insulation Resistance	Termination	Probable Cause[b]
IH317I J4/S-K to T	FR-15WW	$<10^6$	Relay	A
IT1535I J5/E to F	FR-15WW	$<10^6$	Transmitter	A
IT2312I J9/p to h	FR-15AA	$<10^6$	Transmitter	A
IT2457I J8/R to Z	FR-15AA	$<10^6$	Transmitter	A
IT2459I J5/p-n to h	FR-15WW	$<10^6$	Transmitter	A
MB200C TB3/28 to gnd	FR-9HH	$<10^6$	Limit Switch	A
MB200C TB3/29 to gnd	FR-9HH	$<10^6$	Limit Switch	A
MD68C TB4/24 to gnd	FR-9JJ	$<10^6$	Limit Switch	A

a. Hyphen in connection ID means these terminals connected together during measurement.

b. A - contaminated or wet leakage path
B - possible metallic conduction path

resistance meter, having a lower limit of 10^6 ohms. The other values were measured with a meter having only low resistance ranges.

The cause of the low insulation resistance values is consistent with corrosion effects and foreign contamination caused by water intrusion, but this remains to be confirmed. It is not consistent with radiation damage because the change is too large. A test reported in Reference 2 showed only a 10% decrease for a length of FR-15AA cable exposed to 4.4×10^7 rads.

The resistance of a wet leakage path can be low but not well defined because its value depends on the measuring technique. This is believed to be caused by electro-chemical action that effectively adds to or subtracts from the actual resistance value through the electrical current produced.

Contaminated leakage paths are also expected to cause low insulation resistance measurements. Contamination is caused by deposits from evaporating water, dust, grease, and other foreign materials that are not well defined; therefore the path's resistances are not predictable. Because of these uncertainties, the resistance range over which either wet or dirty leakage paths are likely, will be large. Except for the two measurements with less than 30 ohms, all the low resistance values are considered to be caused by either wet or dirty leakage paths. The two values of less than 30 ohms are so much smaller than the other values that another cause seems likely, perhaps a metallic conduction path. Since these two values are easily discernible on the TDR, it might be possible to use the TDR to locate where the low values occur, if they are localized. The TDR is not normally used on the terminals measured for insulation resistance because the high resistance values are not discernible on the TDR display.

In summary, the low insulation resistance anomalies can be characterized as being caused by contaminated or wet leakage paths, or possible metallic conduction paths.

Open or Near-open Loop Resistance

Open or near-open loop resistance was not considered for circuits terminated by transmitters, switches, or relays. Transmitters were ignored because they were unpowered; therefore the resistance values are not predictable because the circuit becomes nonlinear and values vary with the type of ohmmeter circuit, scale used, and polarity of leads. Laboratory measurements on a single Foxboro unit varied from 28.6K ohms to greater than 500M ohms. The switches and relays were not considered because some of them were supposed to be normally open. All cables with this type of anomaly are listed in Table 5. The TDR length was included to show where the opens were located. All opens appear to be located at the penetrations based on the zero TDR lengths. The near-open loop resistance was also seen as an open by the TDR because impedance values much greater than 50 ohms are indistinguishable from opens.

In situ data indicates that circuits H337C and H359C have experienced serious degradation at the reactor building penetration inner liner box. The dc loop resistance in conjunction with the TDR indicates open or near open conditions at these locations. This data is consistent with data taken independently during 1981. Both of these cables are routed through penetration R405 which is at the 292-ft elevation Azimuth 52 degrees 13 minutes. This places the penetration in a direct steam path from the rupture disk of the reactor coolant drain tank. It is believed that this was a major factor for the severe degradation.

Other in situ data taken from this area indicate that the phenomenon of open or near open circuits at the penetration occurs for several cables. Considering that these circuits are connected inside the penetration terminal box and the circuits have opens or near opens gives an indication of the severity of environmental conditions around the southwest corner at the basement elevations.

TABLE 5. CIRCUITS WITH OPEN OR NEAR OPEN (ORDER OF 10^6 ohms) LOOP RESISTANCE

Cable and connection ID	Loop resistance (ohms)	Termination	TDR length
H337C TB1/1-4	$>1 \times 10^7$	Current transformer	0[a]
H359C TB1/8-10	Open	Current transformer	0
H359C TB1/9-10	$>1.5 \times 10^7$	Current transformer	0

a. A zero TDR length indicates the open is at the penetration.

High Loop Resistance

In evaluating circuits with anomalies of high loop resistance, two selection criteria were considered. First, a circuit was considered abnormal when its loop resistance exceeded twice the expected value. This limit was chosen to define an anomaly because the expected value could not be accurately determined, due to uncertainties in documented lengths, cable resistance, and termination resistance. Second, a circuit was considered abnormal if its resistance was less than 10^8 ohms, when the expected value was an open circuit. Transmitter circuits were not considered in this evaluation because of uncertainties in their resistance in the unpowered state.

Table 6 lists circuits with high resistance anomalies. Six of these circuits appear to have closed contacts that exhibit high resistance from corrosion; whereas two circuits, H303I and H315I, appear to have open contacts with high resistance leakage paths caused by moisture and mineral deposits.

Cable S0168P terminates in a delta connected load (heaters). An evaluation of the loop resistance measurements performed on the various elements of the delta load indicate that one element of the delta is open.

The high dc loop resistance of cable MM131P correlates with a distortion at the end instrument in the TDR data and suggests a poor connection at the motor. However, other data is inconsistent and could suggest electro-chemical effect or bad data. This in situ data should be repeated. If the repeated data are consistent, additional information could come from reactor building inspections or measurements, which should be made at the motor to verify the expected cause of the anomaly.

TDR Anomalies

TDR records, as a function of time, voltage reflected back from a voltage step sent down a cable. The voltage reflected back from each point

TABLE 6. CIRCUITS WITH HIGH LOOP RESISTANCE

Cable and connection ID	Loop resistance Measured	Loop resistance Expected	Termination	Comments
H293I J2/p-n	63.8	3.6	Level switch	See a (footnote)
H303I J3/B-C	2.88×10^6	Open	Level switch	See b
H315I J4/A-E	6.57×10^7	Open	Flow switch	See b
H317I J4/p-n	108.9	2.1	Level switch	See a
MB149C TB3/10-13	1.533	0.37	Limit switch	See a
MB200C TB3/28-29	35.2	0.41	Limit switch	See a
MP313C TB4/20-21	778.6	0.65	Fuel Handling Transfer Carriage	Termination unknown
S0168P TB8/1-2 TB8/1-3 TB8/2-3	14.7 29.4 14.6	10.2 10.2 10.2	Pressurizer heater	Open heater element; see c
MM131P TB1/22-23	171.0	42.7	Motor	Inconsistent data
MM131P TB1/22-24	179.9	42.7	Motor	Inconsistent data

a. Closed with corroded switch contacts.

b. Open with corroded or contaminated switch contacts.

c. Heater element resistances calculated from these terminal values show one heater element open (between TB8/1-3) and two good.

is a measure of the impedance of that point. This allows the TDR to show information about each point along a cable system. Using the TDR data, anomalies can be identified with a specific point in a circuit. Anomalies are caused by cable opens and shorts, poor connections, water in cables, open or shorted terminations, and other similar circuit conditions.

Certain cables in penetration R607 had similar TDR anomalies caused by water in the section of the cables near the penetration. The anomalies were seen on the TDR displays as a voltage level lower at the first part of the cables than for the remainder of the cables. Figure 15 shows a TDR display typical of all cables showing this type of anomaly. This wet section is easily identified in Figure 15 and can be used to estimate the length of cable with lowered characteristic impedance (a phenomenon resulting from this anomaly). The anomaly is consistent with increased dielectric constant, as would result from water intrusion in a cable. The increased dielectric constant also causes the velocity of propagation to decrease. Since the independent variable for a TDR display is time, distance is calculated using velocity of propagation. Looking at a TDR display with time as the independent variable will give a distorted measure of distance when the dielectric constant changes, as it does with a wet section of cable. The wet section will appear longer than it would if dry. Based on the estimated change in dielectric constant, cable lengths should appear about 2% longer than if they were all dry. Since cable lengths are not known to this accuracy, this error in length is ignored and length calculations are based on dry dielectrics. Table 7 gives the calculated lengths of the wet section for each cable. The wet sections were related to the cable routes as shown in Figures 16 through 19, the common region being penetration R607 and about 50 ft thereafter except for IT4121I. Table 7 also shows the percent change in characteristic impedance in the anomaly section for each cable.

In conclusion, there is evidence that a cable is wet for the lengths indicated. Since several cables are shielded, the effects of conduits and metal cable trays should have very little effect on the TDR displays.

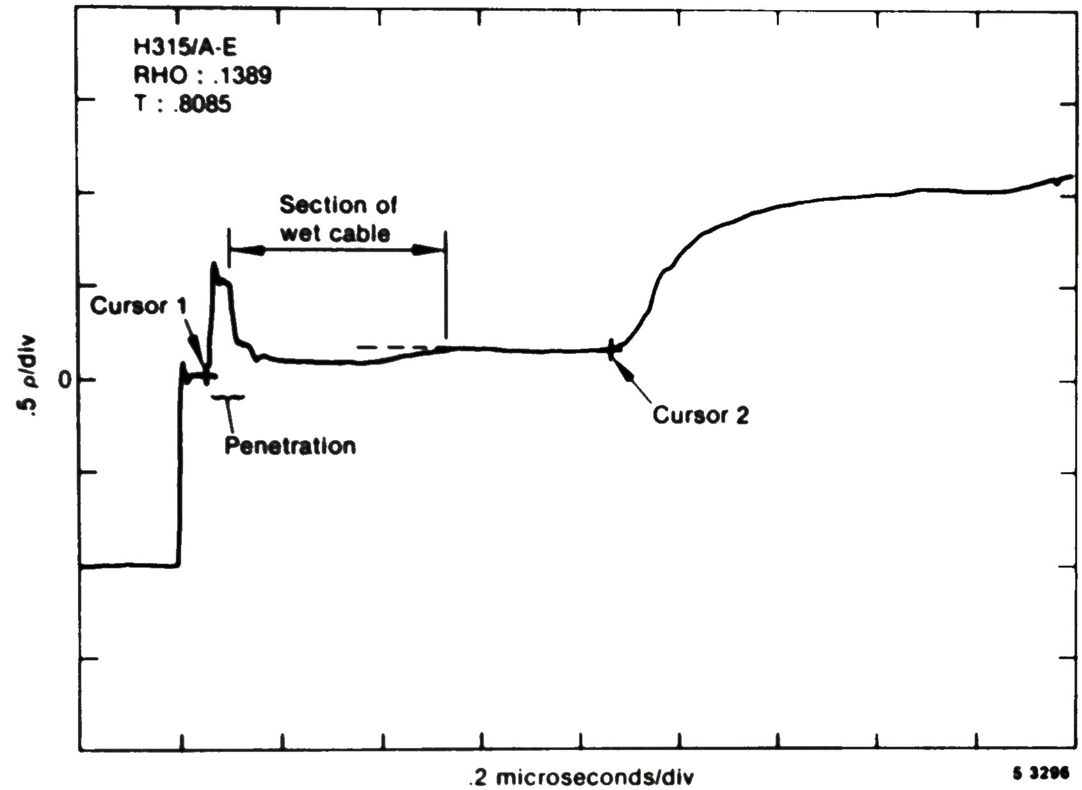


Figure 15. TDR display showing the effects consistent with moisture in a section of cable (H315I).

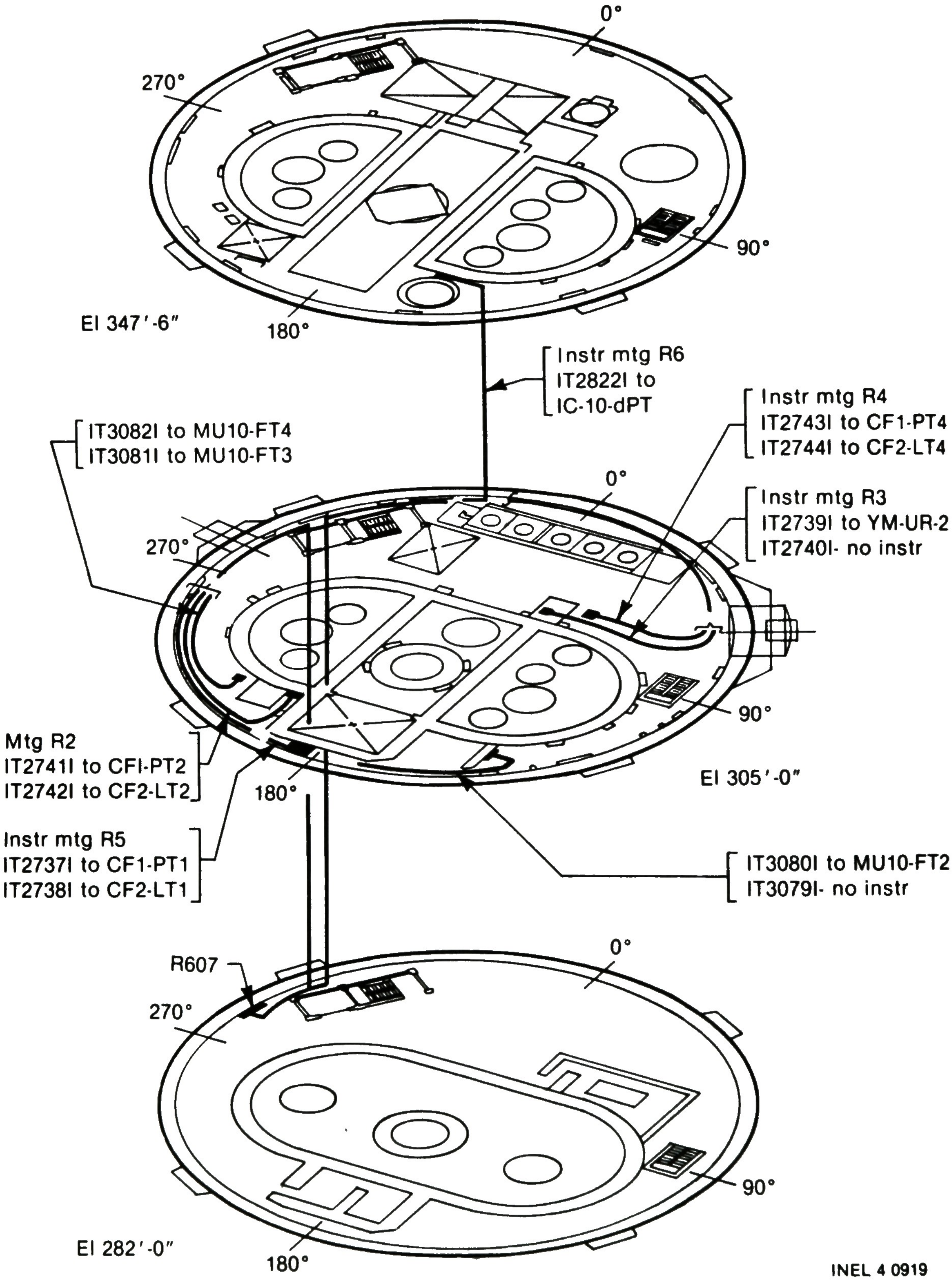


Figure 16. Orientation of penetration R607 and cable runs in the reactor building (sheet 1).

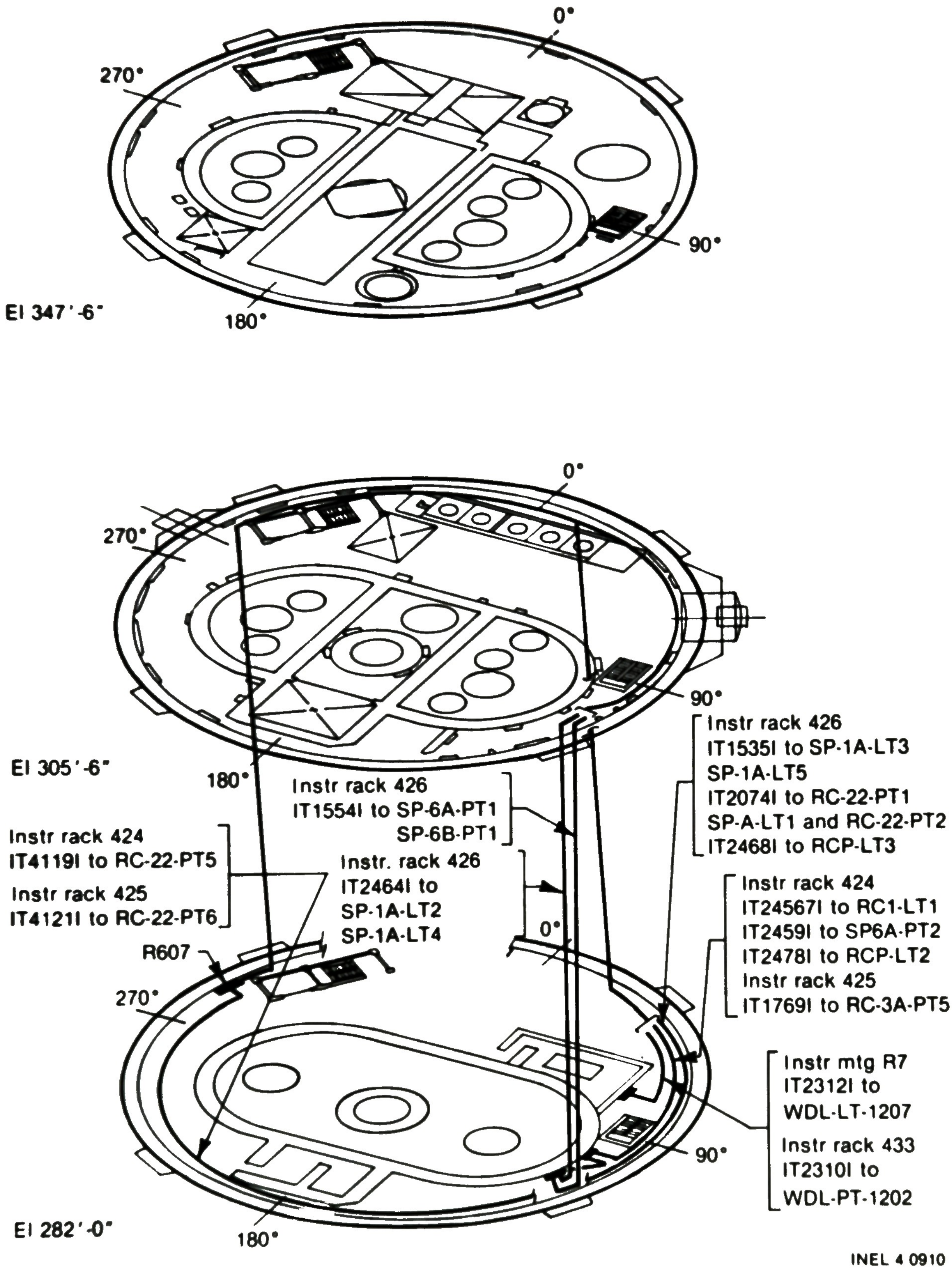


Figure :7. Orientation of penetration R607 and cable runs in the reactor building (sheet 2).

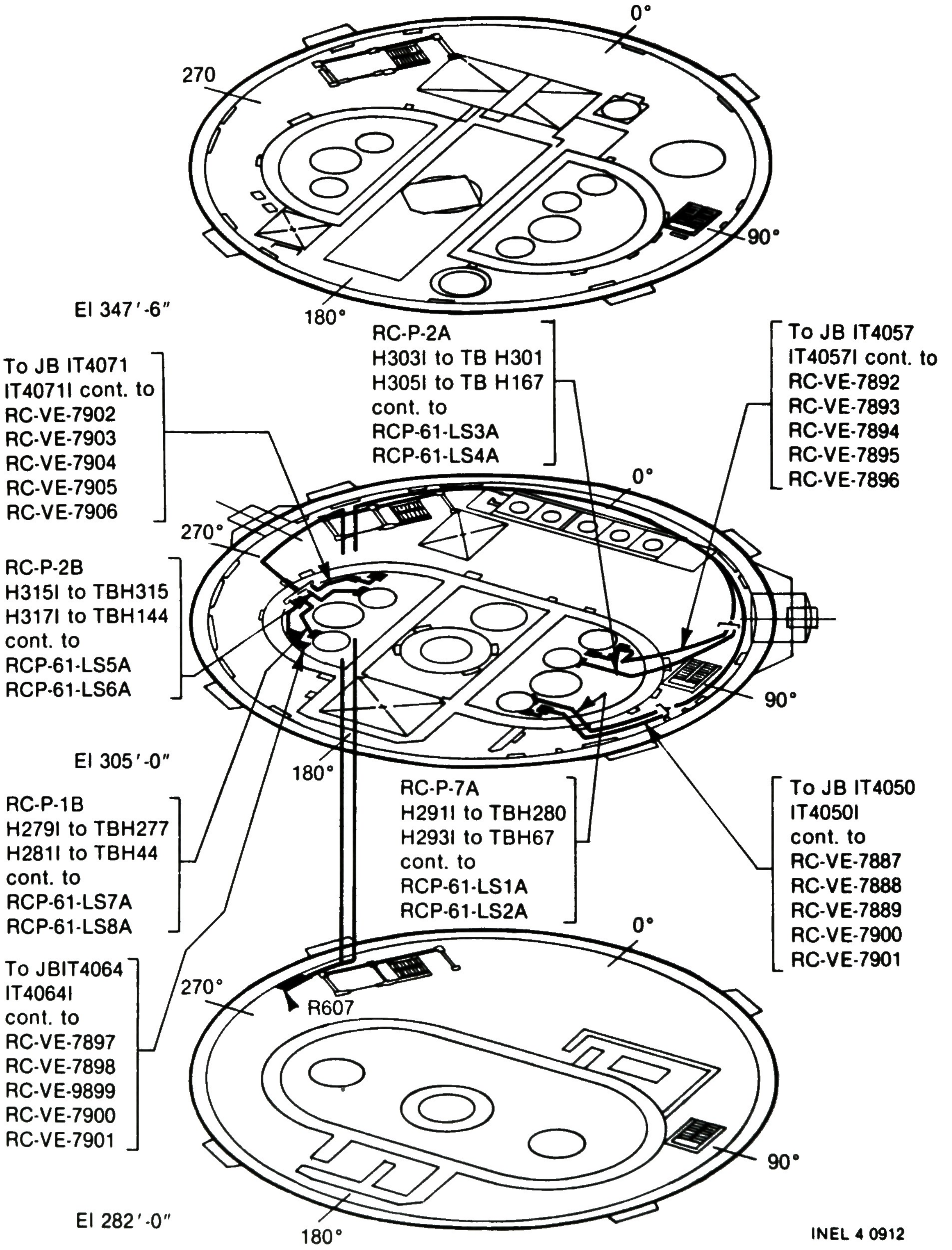


Figure 18. Orientation of penetration R607 and cable runs in the reactor building (sheet 3).

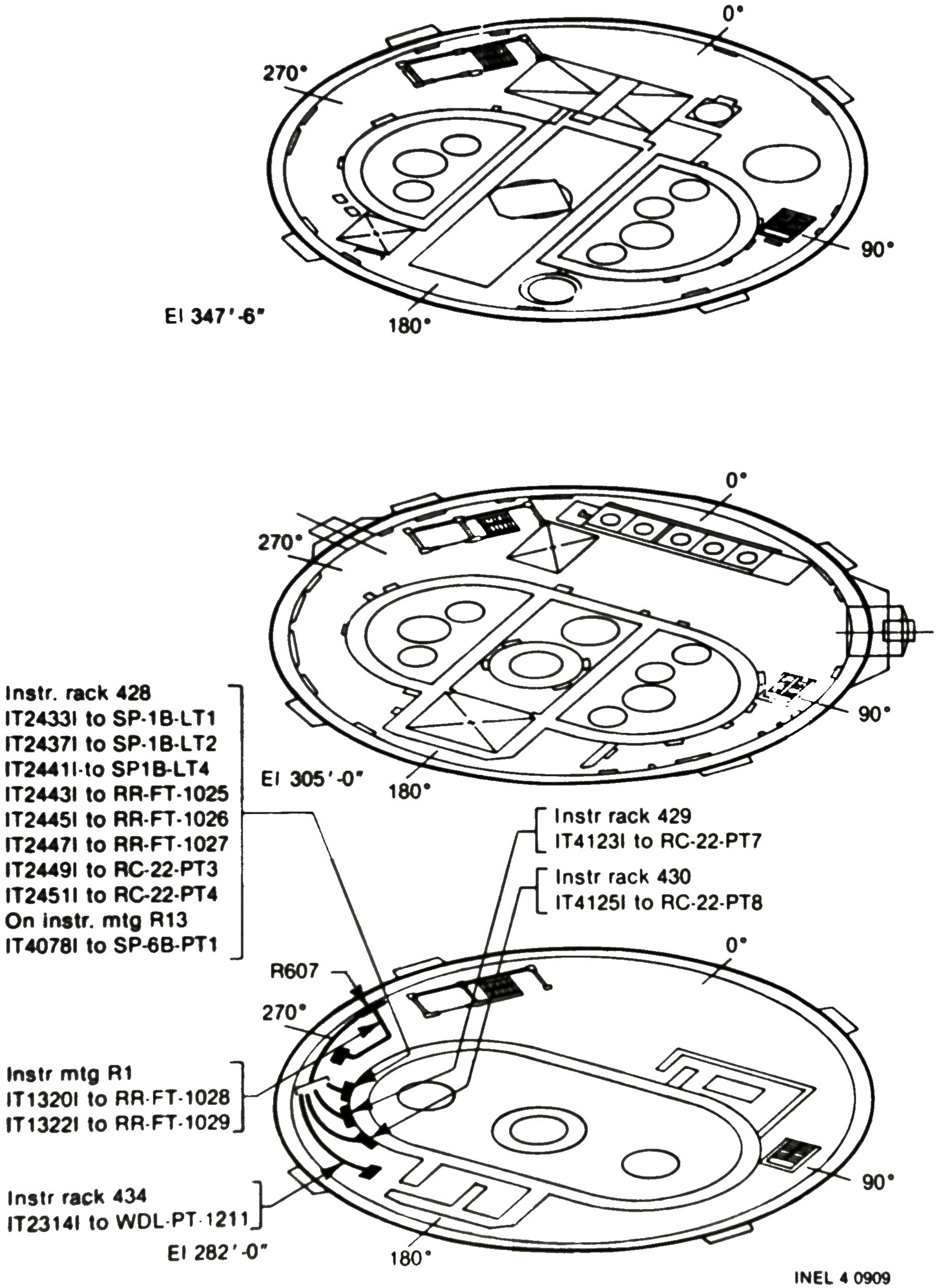


Figure 19. Orientation of penetration R607 and cable runs in the reactor building (sheet 4).

TABLE 7. CABLES WITH TDR ANOMALIES

Cable/Connection	Location of offset (end of transition) Time (ns)	Distance (ft)	Change in Characteristic Impedance (%)
H315I:J4/A-E	449	125	-14.6
H315I:J4/R-Z	441	123	-8.5
H317I:J4/g-a	418	124	-9.2
IT1554I:J9/S-K	410	122	-8.6
IT2310I:J9/k-r	402	122	-10.4
IT2312I:J9/p-n	402	122	-10.6
IT2822I:J9/f-m	394	119	-9.8
IT3079I:J11/H-D	391	117	-7.3
IT3079I:J11/H-J	391	117	-3.1
IT3079I:J11/J-D	391	117	-5.8
IT3080I:J11/R-X	391	117	-6.7
IT3080I:J11/R-Z	391	117	-6.6
IT3080I:J11/X-Z	391	117	-6.9
IT3081I:J11/b-a	406	121	-4.4
IT3081I:J11/b-g	394	117	-4.1
IT3081I:J11/a-g	---	---	-7.5
IT4121I:J8/L-M	254	77	-16.8

Low characteristic Impedance and High Capacitance

Changes in characteristic impedance were not used as anomalies because they must be compared to an absolute reference. In Reference 1, the reference used was the characteristic impedance of a control cable. The control cable was, in most cases, a single sample from spare supply. At this time, it is believed that the cable was not a good reference due to variations in the characteristic impedance resulting from variations in manufacturing techniques. The characteristic impedance for the cables was not specified or directly controlled (except for coaxial cables) by the manufacturers. Without statistics on a large number of samples from different manufacturers, the measurement of a single cable sample is not believed to be suitable as an absolute reference. It is also difficult to measure characteristic impedance (Z_0). Appendix B discusses this and a possibility for decreasing the difficulty. Several cables were considered to have low characteristic impedance in Reference 1, the most common explanation being water in the cables; however, visual inspection of areas near these cables has revealed no evidence of water damage[3]. Without any specific manufacturer control on Z_0, and apparently no water damage in the appropriate cable penetrations or terminal boxes, low characteristic impedance should not be considered as a reliable indication of an anomaly. It is, however, considered along with other factors when assessing the circuits.

Manufacturers of the type of cable used in TMI-2 do not specify or directly control cable capacitance of most cables other than coaxial cables. Capacitance was only measurable on in-containment cables with open circuit terminations. Capacitance is also not a reliable anomaly indicator for the same reasons given for Z_0 in the preceding paragraph. However, the capacitance is used in conjunction with other indicators to assess circuit condition when gross capacitance changes occur.

When available, capacitance and characteristic impedance, along with capacitance anomalies, were used to assess the circuits. Only circuits with nearly open circuits seem to give reliable capacitance measurements, so only those with loop resistance values of 100k ohms or more were evaluated. Table 8 lists these circuits and the parameters used in their evaluation. One environmental effect likely to be identifiable from capacitance and characteristic impedance is water intrusion of the cables. Water intrusion would raise the capacitance, lower the characteristic impedance, increase the dissipation factor, and decrease the velocity of propagation, as compared to the same cable dry. Table 8 shows the capacitance change as percentage deviation from the expected cable capacitance. The expected cable capacitance was computed from the documented length and the capacitance per foot measured on a control cable. When capacitance measurements were available from either two control cables of the same type or adjacent and separated conductors in a multiconductor cable, the minimum and maximum values were both considered and the in situ measurement deviation was based on the closest value. The difference between measured and expected capacitance is given in nF. The maximum control cable capacitance was used to derive the difference. Only positive differences were used, because this column in the table was included to show which capacitance deviations might be caused by terminating devices. The table also shows for comparison, the length as determined from the TDR data and the documented length. The installed length was cut to fit. In Table 8, "Z_0 measured" was the characteristic impedance of the in situ cable as determined from the TDR data. "Z_0 low control" and "Z_0 high control" were characteristic impedance values for the control cables. If more than one measurement was made, either on two cables or two pairs of conductors within a multiconductor cable, "Z_0 low control" was the minimum value and "Z_0 high control" was the maximum value found. If only one measurement for a control cable type was made, these values were equal.

Because circuits with unpowered active devices as terminations had wide variation in measurements and were not predictable, most were not used when evaluating circuits by capacitance anomalies. However, some that had high impedance (measured) which would not obscure the cable capacitance were included in Table 8. Of the 53 circuits shown in Table 8, 20 were for active circuits. Ten of the circuits with active terminations showed no

Table 8 Capacitance and Characteristic Impedance Anomalies

Cable type	Cable	Terminal	Instrument	Insulation resistance (ohms)	Diss factor	Delta capac (%)	Capacitance difference (nF)	Z_0 meas (ohms)	Z_0 low control (ohms)	Z_0 high control (ohms)	Pull-slip length (ft)	TDR length (ft)	Comments
FR-13AA	IT2382I	D-D	NI-6	15E10	0.02	32.15	1.35	66.33	72.7	72.7	255	224.59	See note a
FR-13AA	IT2384I	EE	NI-6	1.6E11	0.	44.1	1.86	67.04	72.7	72.7	256	227.83	See note a
FR-15AA	IT1320I	J11/A-E	RR-FT-1028	8.2E7	0.03	28.81	0.5	54.36	62.1	78.7	60	42.57	See note a
FR-15AA	IT2310I	J9/K-R	WDL-PT-1202	1.8E9	0.06	11.97	1.11	62.37	62.1	78.7	324	278.46	See note a
FR-15AA	IT2366I	TB2/2-3	RC-3A-PT2		0	-0.48	-0.02	54.76	62.1	78.7	170	152.56	OK
FR-15AA	IT2443I	J8/A-E	RR-FT-1025	1.5E7	0.05	73.63	2.13	63.05	62.1	78.7	101	78.58	See note a
FR-15AA	IT2445I	J8/B-C	RR-FT-1026	2.6E6	0.05	92.16	2.17	68.57	62.1	78.7	82	74.73	See note a
FR-15AA	IT2447I	J8/D-J	RR-FT-1027	2.5E5	0.28	89.18	2.1	57.06	62.1	78.7	82	70.01	See note a
FR-15AA	IT2449I	J8/P-N	RC-22PT3	1.4E7	0.14	109.61	2.58	54.93	62.1	78.7	82	69.13	See note a
FR-15AA	IT2737I	J7/F-M	INSTRUMENT REMOVED	7E7	0.02	-65.56	5.79	61.09	62.1	78.7	304	240.51	Short cable per TDR so OK
FR-15AA	IT2739I	J7/6-A	YM-UR-2	0	0.	4.32	0.38	49.67	62.1	78.7	306	286.64	OK
FR-15AA	IT27401	J7/P-N	No INSTR.	2.0E9	0	5.01	0.44	50.92	62.1	78.7	306	287.82	OK
FR-15AA	IT2742I	J7/B-C	INSTRUMENT REMOVED	5.0E9	0.01	7.28	0.58	47.44	62.1	78.7	280	245.26	OK
FR-15AA	IT4119I	J8/K-R	RC22-PT5	3.75E5	0.14	10.85	1.29	75.66	62.1	78.7	416	286.87	OK
FR-15AA	IT4121I	J8/L-M	RC22-PT6	3.3E3	0.07	30.4	3	75.31	62.1	78.7	344	249.13	See note a
FR-15AA	IT4123I	J8/N-P	RC22-PT7	3.5E7	0.03	24	0.15	69.08	62.1	78.7	156	82.42	OK
FR-15AA	IT4125I	J8/C-D	RC22-PT8	1.4E5	0.05	-37.8	2.06	68.74	62.1	78.7	182	102.52	Short cable per TDR so OK
FR-15BB	IT3079I	J11/J-D	MU10-FT1(- & L)	3.0E9	0.02	22.69	2.46	75.53	63.1	63.1	380	349.17	OK
FR-15BB	IT3079I	J11/H-J	MU10-FT1(+ & -)	3.1E9	0.02	22.97	2.49	76.55	63.1	63.1	380	350.36	OK
FR-15BB	TD592I	TB10/1-2	RB-TE-3279	5.0E8	0.01	99.91	-10.85	117.22	63.1	63.1	380	0.42	No cable
FR-15HHH	H305I/H308C	J3/S-K	RC-P-2A	3.6E9	0.03	-19.81	-2.76	62.35	72.5	91	370	299.28	Short cable per TDR so OK
FR-15VV	H291I	J2/A-E	RCP58-FS1	< 10.E6	0.13	-51.87	-6.15	41.16	57.06	63.4	390	390.82	Unexplained low C and high dissipation
FR-15VVV	H2791I	J1/D-J	RCP60-L57	0	0.02	2.1	0.15	55.49	64.6	64.6	232	228.82	OK
FR-15VVV	H303I	J3/B-C	RCP-60-LS3	< 10.E6	0.12	6.69	0.66	57.56	64.6	64.6	330	309.88	OK
FR-15VVV	H303I	J3/A-E	RCP-58-FS3	NA	0.11	11.32	1.12	58.07	64.6	64.6	330	310.99	OK
FR-15VVV	H315I	J4/A-E	RCP-58-FS5	<0.E6	0.14	24.09	2.07	66.13	64.6	64.6	245	210.46	Unexplained slightly high C
FR-15WW	H281I/H284C	J1/P-N	RC-P-1B	9.0E8	0.06	46.35	4.51	60.15	63.06	63.06	196	199.11	Maybe wet but Zo not low
FR-15WW	H293I/H296C	J2/S-K	RC-P-1A	NA	0.45	31.96	4.4	53.88	63.06	63.06	387	351.97	Maybe wet
FR-15WW	H3171/H320C	J4/S-K	RC-P-2B	< 10.E9	0.04	2.59	0.25	56.06	63.06	63.06	200	'70.24	OK
FR-15WW	IT1535I	J5/D-J	NO INSTR	7.0E8	0.32	-7.88	-0.89	79.33	63.06	63.06	376	373.71	OK except dissipation factor high
FR-15WW	IT1554I	J9/A-E	SP-6A-PT1	8.7E7	0.12	3.96	0.44	77.07	63.06	63.06	37u	366.93	OK
FR-15WW	IT1554I	J9/S-K	SP-6A-PT1	1.7E8	0.01	7.86	-0.87	77.86	63.06	63.06	370	368.12	OK
FR-15WW	IT1554I	J9/D-J	SP-6A-FT1	5.4E8	0.02	-9.12	1.01	79.23	63.06	63.06	370	368.12	OK
FR-15WW	IT2074I	J6/G-A	RC22-PT2	7.5E6	0.05	53.15	6.06	77.76	63.06	63.06	381	373.57	See note a
FR-15WW	IT2459I	J5/S-K	SPARE	1.2E8	0.02	-7.04	-0.76	78.35	63.06	63.06	380	359.76	OK
FR-15WW	IT2464I	J6/L-M	NO INSTR	1.0E10	0.02	-11.44	-1.29	79.22	63.06	63.06	376	373.57	OK
FR-9EE	H289C	TB3/7-8	RCP56-PS2/PS5/FS2	3.0E8	0.46	34.95	1.73	176.24	94.3	107.5	228	228.51	High C prob due 3 sw but diss. high
FR-9EE	H301C	TB3/9-10	RCP56-PS7/10&59FS4	2.8E8	0.13	124.17	6.47	70.48	94.3	107.5	240	288.65	High C prob due 3 sw but diss. high
FR-9EE	IT2810C	TB3/11-12	AH-TS-5024	9.5E8	0.05	114.93	7.29	51.11	94.3	107.5	292	303.42	Maybe wet, high C, low Zo
FR-9EE	MC125C	TB13/1-2	CF-V1A LMS	2.8E8	0.07	110.31	4.89	51.73	94.3	107.5	204	194.56	Maybe wet, high C, low Zo
FR-9EE	MD125C	TB2/22-23	CF-V1B LMS	2.7E7	0.06	139.45	6.18	49.73	94.3	107.5	204	213.89	Maybe wet, high C, low Zo
FR-9HH	MB133C	TB3/6—7	SP HEATER	2.8E7	0.05	38.37	0.79	60.22	82.3	126.	88	91.65	Probably OK

S 3342

Table 8. Capacitance and Characteristic Impedance Anomalies

Cable type	Cable	Terminal	Instrument	Insulation resistance (ohms)	Diss. factor	Delta capac. (%)	Capacitance difference (nF)	Z_0 meas. (ohms)	Z_0 low control (ohms)	Z_0 high control (ohms)	Pull-slip length (ft)	TDR length (ft)	Comments
FR-9HH	MB149C	TB3/15-16	SP. HEATER	3.4E9	0.05	32.07	0.83	55.88	82.3	126.	110	108.86	Probably OK
FR-9HH	MB193C	TB3/24-25	WDL-V271		0.04	38.72	1.21	55.46	82.3	126.	134	137.18	Probably OK
FR-9HH	MB200C	TB3/33-34	SP. HEATER		0.22	37.5	1.09	53.7	82.3	126.	124	134.42	Probably OK
FR-9HH	MS130C	TB6/6-7	CF-V2B	7.5E8	0.02	29.53	2.44	56.19	82.3	126.	354	353.09	OK
FR-9HH	MS45C	TB6/24-25	RC-V3	1.5E8	0.04	50.06	4.14	56.32	82.3	126.	354	381.81	OK
FR-9HH	MS76C	TB8/19-20	RC-V117	2.4E9	0.03	33.31	2.8	57.94	82.3	126.	360	368.45	OK
FR-9JJ	MB437C	TB9/24-32	MU-V1B	1.75E5	0.22	-6.95	-0.54	45.48	69.1	112.	168	169.22	OK
FR-9JJ	MB437C	TB9/33-34	SP. HEATER	1.05E7	0.05	-11.5	-3.14	48.04	69.1	112.	168	168.23	OK
FR-9JJ	MD68C	TB4/33-34	SP. HEATER	2.96E4	0.2	9.99	-1.82	47.94	69.1	112.	152	152.81	OK
FR-9KK	MP313C	TB4/10-11	FH-A4B LMS	1.8E7	-0.06	-4.53	-0.39	48.88	72.8	114.6	190	211.31	OK
FR-9KK	MP313C	TB4/14-15	FH-A4B LMS		-0.12	-10.76	-0.94	51.49	72.8	114.6	190	200.53	OK

Note a. Extra capacitance probably due to active termination whose capacitance is not known and not consistent.

5 3343

significant anomalies. The other 10 had high capacitances, which were probably caused by the terminations, since the amounts attributed to the terminations were mostly 1 to 3 nF, with one case of 6 nF.

Five cables had only one or two symptoms of a wet cable and are listed as "maybe wet."

In summary, Table 8 lists circuits that were examined for capacitance and characteristic impedance anomalies, and gives conclusions. Only five circuits were found that have enough symptoms to be considered possibly wet.

Conclusions

Of 144 cables, 38 insulation resistance measurements were found to be less than one megohm. Of these, 36 were attributed to wet or dirty leakage paths and two to damaged insulation.

Of 361 loop resistance measurements made, 2 circuits were open, or effectively so, and these opens were likely caused by corrosion of their connectors. Twelve circuits had high loop resistance, of which seven were believed to be caused by switch contact closure problems and two by contact opening problems. A pressurizer heater element or its leads were open, and two circuits had high loop resistance consistent with a connection problem common to them.

Seventeen circuits, all in R607, had offsets at the start of their TDR displays. This is consistent with wet cables, and is reasonable since the bottom of R607 was under water.

We believe that all circuits listed could be operational, with exception of the two open circuits, the open pressurizer heater, and the pressurizer heater with very low insulation resistance.

FUNCTIONAL ANALYSIS

The in situ measurements were used to find anomalies that indicated problems with the operation or functioning of the circuits measured. Anomalies were found by comparing the measured values to a reference value. For this type of data, probably the best reference value would be data from measurements made on each circuit when it was known to be good. Since these were not available, reference values were calculated from measurements made on control cables, device specifications, or reasonably expected values.

The types of circuits are based on the terminating devices and their function. The types are listed below.

- Motors
- RTDs
- Transmitters and loose parts monitors
- Pressurizer heaters
- Current transformers
- Neutron detectors
- Switches and relays for alarms and annunciators.

Effects of Parameter Variations on Circuit Functionality

Although numerous kinds of measurements were made to evaluate the TMI circuits, not all were useful for determining the functional condition of the circuits. This is illustrated in Table 9 by the small effect some parameters have on the functioning of some the circuits.

TABLE 9. EFFECTS OF DEGRADED PARAMETERS ON CIRCUIT FUNCTIONING

Parameter	Effect on Functioning
Insulation resistance	Low values cause ground fault currents and shock hazards for pressurizer heaters
Loop resistance	See text
Capacitance	Alters motor torque
Inductance	No feasible fault would cause large enough change to effect circuit operation
TDR results	
Char. imped.	No direct effects
TDR length	No direct effects, except for open or shorted cables

As indicated in Table 9, most of the measured parameters do not have important effects on the operation of the circuits. This is because most circuits have very wide margins of safety as far as functioning of the circuits is concerned. Loop resistance does effect all circuits however. These effects are discussed below.

Effects of Loop Resistance on Circuit Operation

An open circuit can cause a circuit to be nonfunctional. Except in the case of a short near the far end of a cable, a small negative deviation from the expected value of loop resistance would not adversely affect circuit operation. A short near the far end of a cable could not be identified from the available data. A small positive deviation from the expected value of loop resistance could be caused by poor contact or a per-unit cable resistance that is larger-than-expected. The effect of the deviation on the operation of the circuit was calculated using specifications of the circuit (out of the reactor building). Large positive deviations in loop resistance were likely caused by poor contact resistance for either connectors or end device contacts. If the termination contacts were open, the operation of the circuit could not be determined. An undesirable shunt resistance across the cable, if small enough, would cause the circuit to be inoperable.

If the termination was a transmitter, loose parts monitor, or another active circuit, the loop resistance was normally high but not well-defined because it was an unpowered active circuit. Operational evaluation based on loop resistance was not attempted for active circuits unless the TDR data showed a short or open at less than the reasonably expected cable length; none did. This is because what appears to the TDR to be a short or open along the length of a cable is very likely just that. It can be a normal active circuit if it appears to the TDR to be at the end of a cable.

For pressurizer heaters, open circuits and loop resistance values near the expected cable resistance are considered inoperable. A high loop resistance would cause reduced heater power, and for certain values, possible fire hazards. Limits for these were calculated.

Functional Analysis by Circuit Type

Circuits requiring the same functional analysis procedures were grouped. The functional analysis procedures and results are discussed in these groups. The group names reflect their function rather than the analysis procedure.

Limit Switches

The circuits of cable MD17C are representative of the circuits in this group. Figure 20 is a schematic of these circuits, showing the reactor building and out-of-reactor building parts.

The circuits are analyzed by computing the worst case values of the circuit parameters that allow acceptable performance. These values are then compared to those measured in situ. If the measured values are better than the worst case values, the circuit is considered functional.

Impedance. The first step is to determine the impedance for each circuit element. As shown in Figure 20, there are two lamp circuits, two contactor coil circuits, and a heater circuit. Each type is considered below.

Lamps--3 watts at 120 volts nominal.

$$R = V^2/P = 120^2/3 = 4800 \text{ ohms}$$

where R is the resistance for one lamp, V is the nominal operating voltage, and P is the power. Since there are two lamps in parallel for each circuit, the total resistance is 2400 ohms for each circuit.

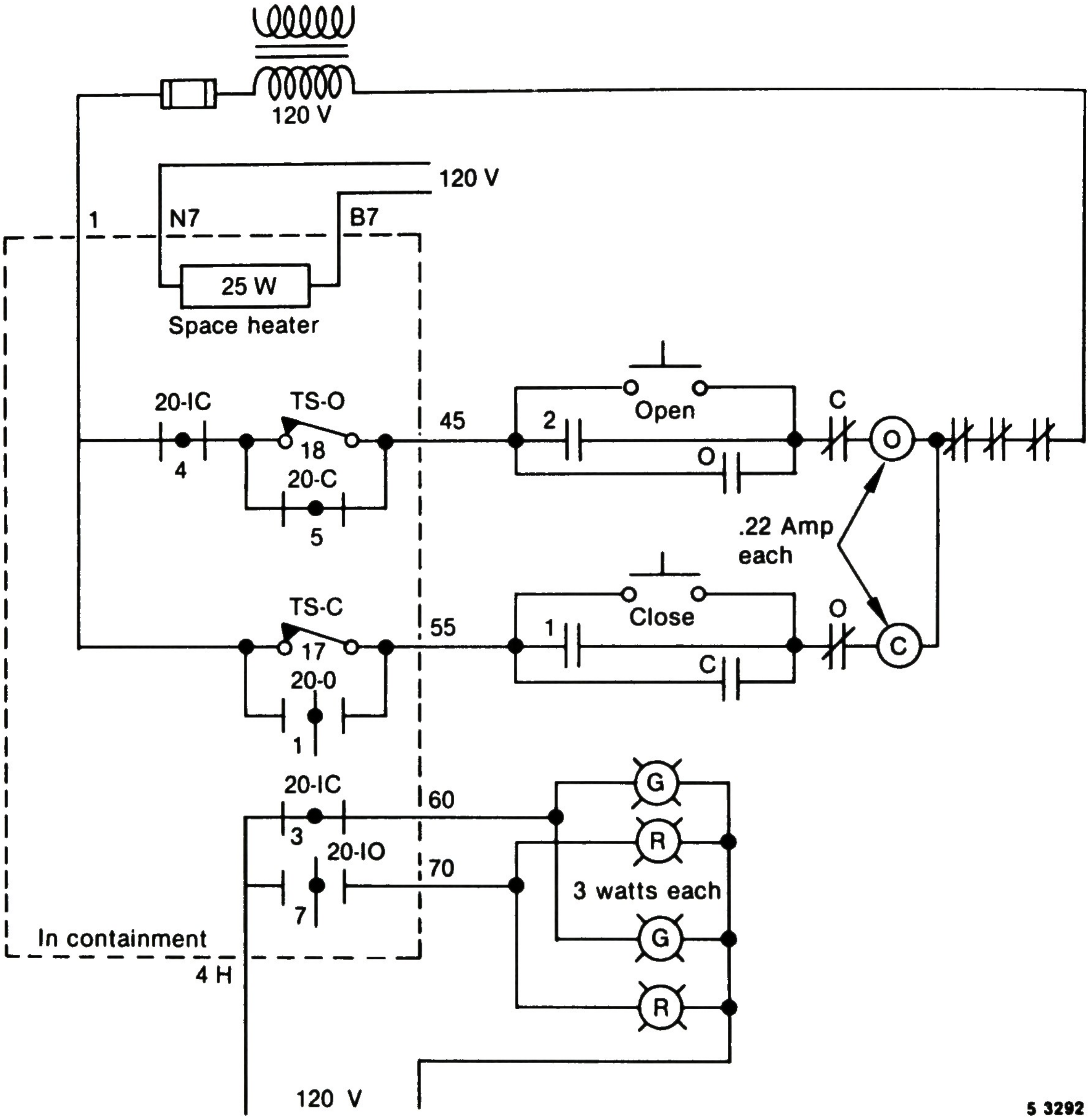


Figure 20. Wiring diagram of typical limit switch circuit showing complete loop.

Contactor Coils--0.22 amperes at 120 volts

$Z = V/I = 120/0.22 = 545$ ohms

where I is the rated current for each contactor coil, and Z is the coil impedance. Only one coil is allowed to be energized at a time, so the above resistance is the value seen when the switches are closed.

Minimum Power or Voltage. The second step is to determine the minimum acceptable power or voltage for each component.

Lamps--Laboratory measurements and observations followed by calculations indicate that the maximum series resistance for visibility of lamps is about 42% of the rated lamp resistance.

Contactor Coils--The minimum contactor voltage used was 75% of nominal, a common minimum starting voltage.

Maximum Allowable Series Resistance. The third step is to determine the maximum allowable series resistance--the resistance required to reduce the voltage or power to the value just calculated.

Lamps--It was determined earlier that the maximum series resistance should be 42% of the lamp resistance, therefore

$R_s = 0.42 \times 2400 = 1008$ ohms.

Contactor Coils--The contactor coil voltage is given by

$V_c = 120\ R_c/(R_c + R_s)$

where V_c is the contactor coil voltage, R_c is the contactor coil resistance, and R_s is the series resistance. This assumes that the contactor coil impedance is predominantly resistive. Solving for R_s to give a contactor coil voltage of 75% of normal gives

$R_s = (R_c/0.75) - R_c = 181.7$ ohms.

The measured values for these circuits were then compared to the maximum values. If the measured values are less than this limiting value, the circuit is considered functional unless there are other indications to the contrary.

As noted earlier, there are two contactor coil circuits, two lamp circuits, and one heater circuit. Table 10 lists the resistances for these circuits for the ten cables with these types of circuits. The open circuits are assumed to be open switches for the lamps and contactor coils.

There are two lamp circuits, both controlled by switches. Since these switches were not under the tester's control, some of them were open and some closed. Whether or not they were in their correct positions is not considered here, since that is not part of the circuit function. All the resistances are much less than the maximum allowed value; therefore, all of the lamp circuits are believed to be functional.

There are also two contactor coil circuits. The 35.2 ohms for cable MB200C is much higher than the resistance for the other contractor coil circuits and is an anomaly, but it should not prevent functioning of this circuit since it is less than the calculated maximum value.

Motors

Circuits for ten three-phase motors for valve positioning and pumps were measured. All were in penetration R505. Figure 21 is a schematic of these circuits. Evaluation was based on motor loop resistance and inductance for each phase, and insulation resistance to the ground.

Since starting should be the most demanding condition for the functioning of a motor, it was checked first. A limit on the minimum starting voltage of 75% of the normal voltage was used. The case of a single bad connection or other cause of series resistance was considered to

TABLE 10. MEASURED LOOP RESISTANCE FOR CABLE CIRCUITS WITH LIMIT SWITCHES (see Figure 20)

Penetration/Cable	Lamp Circuits Max Unless Open No. 1	Lamp Circuits Max Unless Open No. 2	Contactor Circuits 181.7 ohms Max Unless Open No. 1	Contactor Circuits 181.7 ohms Max Unless Open No. 2
R504/				
MB133C	0.20	Open	0.21	Open
MB149C	1.53	Open	0.32	Open
MB193C	0.33	Open	0.34	Open
Open				
MB200C	Open	0.29	35.2	0.34
MB367C	0.34	Open	0.36	Open
MB437C	--	0.44	--	0.44
MD17C	0.48	Open	0.73	Open
MD68C	0.39	Open	0.44	Open
R506/				
MM134C	0.90	Open	0.90	Open
MS22C	0.92	Open	0.90	Open
MS45C	0.96	Open	0.93	Open
MS69C	Open	1.06	Open	1.06
MS76C	0.97	Open	0.99	Open
MS90C	1.57	1.12	1.14	Open
MS130C	0.90	Open	0.92	0.90

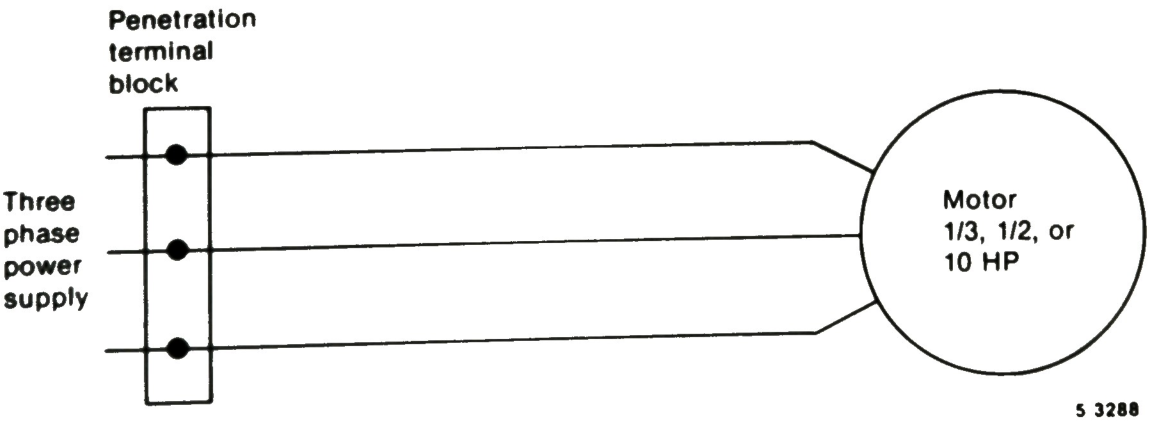


Figure 21. Wiring diagram of motors associated with pumps and motor-operated valves.

determine the order of magnitude of series resistance required to cause starting problems. More complicated cases were not considered because the size of this calculated resistance was much larger than any indicated from measurements. The starting voltage was computed using a series resistance and the motor impedance, as shown in Figure 22. The motor impedance is given by

$$Z_x = (R_m^2 + X^2)^{0.5}$$

and the total impedance by

$$Z_x = [((R_m+R_s)^2 + X^2)]^{0.5}$$

where R_m is the motor resistance, R_s is the series resistance caused by poor connections, and X is the motor reactance. The motor reactance (X) is equal to 2 x Pi x f x L, where f is the power line frequency, L is the motor inductance, and Pi is 3.141589. The motor resistance was found by subtracting the expected cable resistance from the value measured between two terminals and taking 1.5 times the result to give the equivalent delta connected value for a balanced delta circuit. An analogous procedure gave the equivalent motor inductance.

The motor starting voltage was found by analyzing Figure 22. Details are given in Appendix A. This analysis assumed that reactance changes were negligible.

The motors measured were 1/3, 1/2, and 10 hp. The 1/3-hp measurements were about the same values, so a preliminary evaluation was made using an average of the measurements which were 64.1 ohms for the motor resistance and 0.416 henries for the inductance. Using these values, the series resistance, R_s, was calculated as shown in Appendix A, and found to be 32.1 ohms. This series resistance will increase the measured resistance above the total of the cable resistance and the motor resistance. All measured increases were much smaller that this value; therefore, no starting problems were identified. Two resistance measurements were not

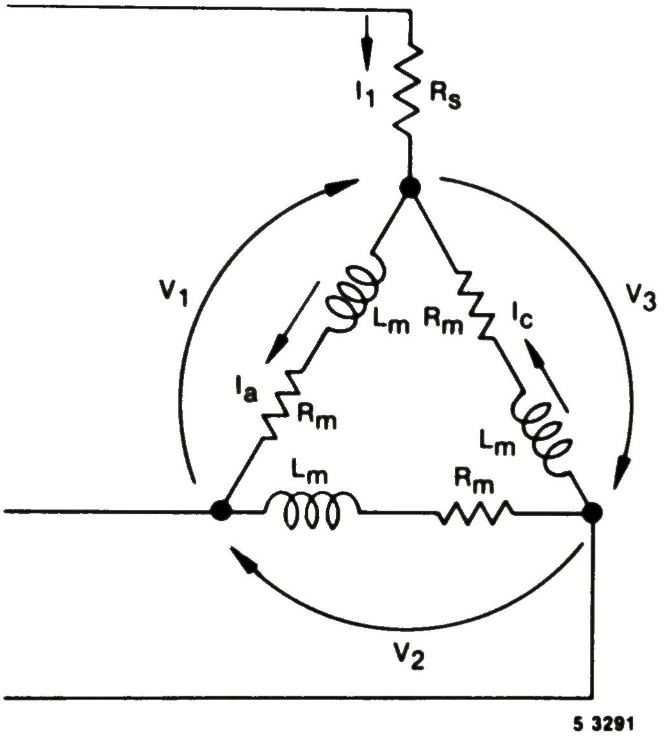


Figure 22. Equivalent circuit of a motor with series resistance used in computing the motor starting voltage.

consistent, possibly because of pickup noise, and they probably indicate circuit problems and should be considered nonfunctional. They were both for Cable MM131P, listed in Table 11.

The 1/2-hp motors were from two manufacturers: four from Tuthill and one from Reliance. Their measurements were different, so separate calculations were made. For the Tuthill motors, the average resistance (delta equivalent) was 33.1 ohms, and the average inductance (delta equivalent) was 0.213 henries. These gave a value of 16.4 ohms for the series resistance required to cause starting problems. For the Reliance motor, the delta equivalent resistance and inductance average values were 39.5 ohms and 0.158 henries. The series resistance calculated was 13.2 ohms. No increases over average values this large for these motors were seen so no starting problems were identified.

Only two 10-hp motors were measured, and their average delta equivalent resistance was 1.237 ohms. The corresponding inductance was 0.0205 henries. The calculated allowable series resistance was 1.58 ohms. Again, there was no evidence of starting problems.

As a further evaluation, the circuits were compared to their averages. For the 1/2-hp motors, the maximum resistance deviation was 2.1%; for the Tuthill 1/2-hp motors, the deviation was 3.8%; and for the Reliance 1/2 hp motor, the three values had 0.5% variation. The 10-hp motors showed more deviation between motors but very little variation between values for one motor, except for the TB3/3-5 measurement on cable MP19P, which was 7.0 % larger than the other two. This cannot be in series with the cable conductors or there would be two values larger than the third. For the same reason, the increase in resistance must be in one leg of a delta connection. Converting the measured resistance values (minus the cable resistances) to delta elements gives 2.73, 2.73, and 3.15 ohms. The high value is 15.4% larger than the other two. Although this should still be an operational circuit, the cause of the increased resistance should be determined. It may be a loose connection that could cause problems.

TABLE 11. FUNCTIONAL CONDITIONS OF THE VARIOUS CIRCUITS TESTED

Cable	Condition	Comments
Motors		
ML78P	Functional	
MM131P	Nonfunctional	Undetermined resistance for connections TB1/22-23 and TB1/22-24
MP19P	Functional	Resistance at motor 15% higher for connection TB3/3-5 than other connections
MP25P	Functional	
MP37	Functional	
MP43P	Functional	
MP45P	Functional	
MP51P	Functional	
MS88P	Functional	
MS128P	Functional	Insulation resistance low; value is 9.3×10^4 ohms; possibly hazardous
RTDs		
TD948I	Undetermined	Appears functional from extrapolated data
Transmitters		
(R406)		
IT2347I	Undetermined	See a (footnote)
T2351I	Undetermined	See a
(R506)		
IT2750C	Undetermined	See a
(R534)		
IT2366I	Undetermined	See a
IT2368C	Undetermined	See a
IT2370C	Undetermined	See a
IT2472I	Undetermined	See a
IT4079I	Undetermined	See a
IT4080I	Undetermined	See a

TABLE 11. (continued)

Cable	Condition	Comments
(R607)		
IT1320I	Undetermined	See a
IT1322I	Undetermined	See a
IT1535I	Undetermined	See a
IT1554I	Undetermined	See a
IT1769I	Undetermined	See a
IT2074I	Undetermined	See a
IT2310I	Undetermined	See a
IT2312I	Undetermined	See a
IT2314I	Undetermined	See a
IT2433I	Undetermined	See a
IT2437I	Undetermined	See a
IT2441I	Undetermined	See a
IT2443I	Undetermined	See a
IT2445I	Undetermined	See a
IT2447I	Undetermined	See a
IT2449I	Undetermined	See a
IT2451I	Undetermined	See a
IT2457I	Undetermined	See a
IT2459I	Undetermined	See a
IT2464I	Undetermined	See a
IT2468I	Undetermined	See a
IT2478I	Undetermined	See a
IT2737I	Undetermined	See a
IT2738I	Undetermined	See a
IT2741I	Undetermined	See a
IT2742I	Undetermined	See a
IT2743I	Undetermined	See a
IT2744I	Undetermined	See a
IT2822I	Undetermined	See a
IT3080I	Undetermined	See a
IT3081I	Undetermined	See a
IT3082I	Undetermined	See a
IT4078I	Undetermined	See a
IT4119I	Undetermined	See a
IT4121I	Undetermined	See a
IT4123I	Undetermined	See a
IT4125I	Undetermined	See a
Loose Parts Monitors		
(R406)		
IT3566I	Undetermined	See a
IT3572I	Undetermined	See a
IT3596I	Undetermined	See a

TABLE 11. (continued)

Cable	Condition	Comments
(R534)		
IT3578I	Undetermined	See a
IT3581I	Undetermined	See a
IT3590I	Undetermined	See a
IT3599I	Undetermined	See a
<u>Pressurizer heaters</u>		
S078P	Functional	
S080P	Nonfunctional	See b
S082P	Functional	
S084P	Functional	
S086P	Functional	
S088P	Functional	
S0139P	Functional	
S0141P	Functional	
S0143P	Functional	
S0145P	Functional	
S0147P	Functional	
S0149P	Functional	
S0156P	Functional	
S0158P	Functional	
S0160P	Functional	
S0162P	Functional	
S0164P	Functional	
S0166P	Functional	
S0168P	Nonfunctional	See c
S0170P	Functional	
S0172P	Functional	
S0174P	Functional	
S0176P	Functional	
S0178P	Functional	
SP27P	Functional	
SP29P	Functional	
SP31P	Functional	
SP129P	Functional	
SP131P	Functional	
SP133P	Functional	
SP135P	Functional	
SP137P	Functional	
SP139P	Functional	
SP142P	Functional	
SP144P	Functional	

TABLE 11. (continued)

Cable	Condition	Comments
SP146P	Functional	
SP148P	Functional	
SP148P	Functional	
SP150P	Functional	
SP152P	Functional	
Current Transformers		
H337C	Nonfunctional	TB1/1-4 open
H348C	Undetermined	Probably functional
H359C	Nonfunctional	TB1/7-10 open
Neutron detectors		
IT2360C	Undetermined	Open inner shield
IT2362I	Undetermined	See a
IT2364I	Undetermined	See a
Switches or relays for alarms and annunciators		
A123C		
WDL-PS-1201-1 & WDL-PS-1201-3	Functional	
H279I		
RCP60-LS7	Cable functional	See d
RCP56-PS16	Functional	
H281I/		
H282C RCP61-LS7A	Functional	
H283C RCP61-LS8A	Functional	
H284C RC-P-1B	Cable functional	See d
H289C		
RCP56-PS2, RCP56-PS5, & RCP59-FS2	Cable functional	See d
H291I		
RCP58-FS1	Cable functional	See d
RCP60-LS1	Functional	
H293I/		
H294C RCP61-LS1A	Functional	
H295C RCP61-LS2A	Functional	
H296C RC-P-1A	Cable functional	See d

TABLE 11. (continued)

Cable	Condition	Comments
H301C		
RCP56-PS7,		
RCP56-PS10, &		
RCP59-FS4	Cable functional	See d
H303I		
RCP58-FS3	Cable functional	See d
RCP60-LS3	Cable functional	See d
H305I		
H306C RCP61-LS3A	Functional	
H307C RCP61-LS4A	Functional	
H308C RC-P-2A	Cable functional	See d
H315I		
RCP58-FS5	Cable functional	See d
RCP60-LS6	Functional	
H317I/		
H318C RCP61-LS5A	Functional	Contacts about 100 ohms
H319C RCP61-LS6A	Functional	
H320C RC-P-2B	Cable functional	See d
IT2810C		
AH-TS-5024	Cable functional	See d
IT2814C		
AH-LS-5006	Functional	
IT2816C		
AH-LS-5007	Functional	
IT2818C		
AH-LS-5008	Functional	
IT3016C		
IC-R-1091	Cable functional	See e
IT3519C		
RC-PS-7361	Functional	
IT3528C		
NM-PS-4174	Cable functional	See d
NM-PS-4175	Cable functional	See d
NM-PS-1454	Functional	

TABLE 11. (continued)

Cable	Condition	Comments

a. Data available are insufficient to determine if circuit is functional, but none of the data shows it nonfunctional.

b. Very low insulation resistance (22.5 ohms) TB7/4-5-6 to ground. Possible fire hazard or ground fault current interrupt causing the the heater to be disabled

c. Open in heater circuit TB8/1-3

d. Open circuit. TDR showed cable not open.

e. Three loop resistance values; one normal, two much higher than expected but in range expected to be functional.

One cable (MS88P) had an insulation resistance of 9.3×10^4 ohms which is less than the IEEE recommended minimum of 1.5×10^6 ohms.

Table 11 summarizes these conclusions.

Pressurizer Heaters

The functional condition of the heaters was determined by comparing the calculated in situ power to the nominal expected power for each heater element. Each heater was made up of three heater elements connected in a delta configuration. Measurements were made between terminals at penetrations R400, R402, and R407. These terminals were connected to the heaters by a length of three-conductor cable and three shorter two-conductor cables (see Figure 23). The two-conductor cables were a part of the heater delta configuration. Measurements made between a pair of terminals at a penetration measured two heater elements in series paralleled by the third element at the end of the cables. So that each heater element could be evaluated, its resistance was computed from the measurements at the terminals. First, the expected cable resistances were subtracted from the resistance measured at each terminal pair. Next, the three heater element resistances were computed from the three modified terminal resistance values. This involved a set of three nonlinear algebraic equations which were solved iteratively on a programmable calculator. The values indicate that the element (or its connection) between terminals 1 and 3 for cable S0168P was open, which meant that it was nonfunctional. Next, the ratio of in situ to expected nominal power was calculated. The expected nominal power was 14 kW at 460 volts. Because of a nearly balanced load, the in situ power was calculated as approximately

$$P_H = R_H(460)^2/(R_H + R_L)^2$$

where P_H is the heater power, 460 is the line voltage, and R_H is the calculated line resistance. The ratio of this power to the expected nominal power was calculated for each heater element, except the open one,

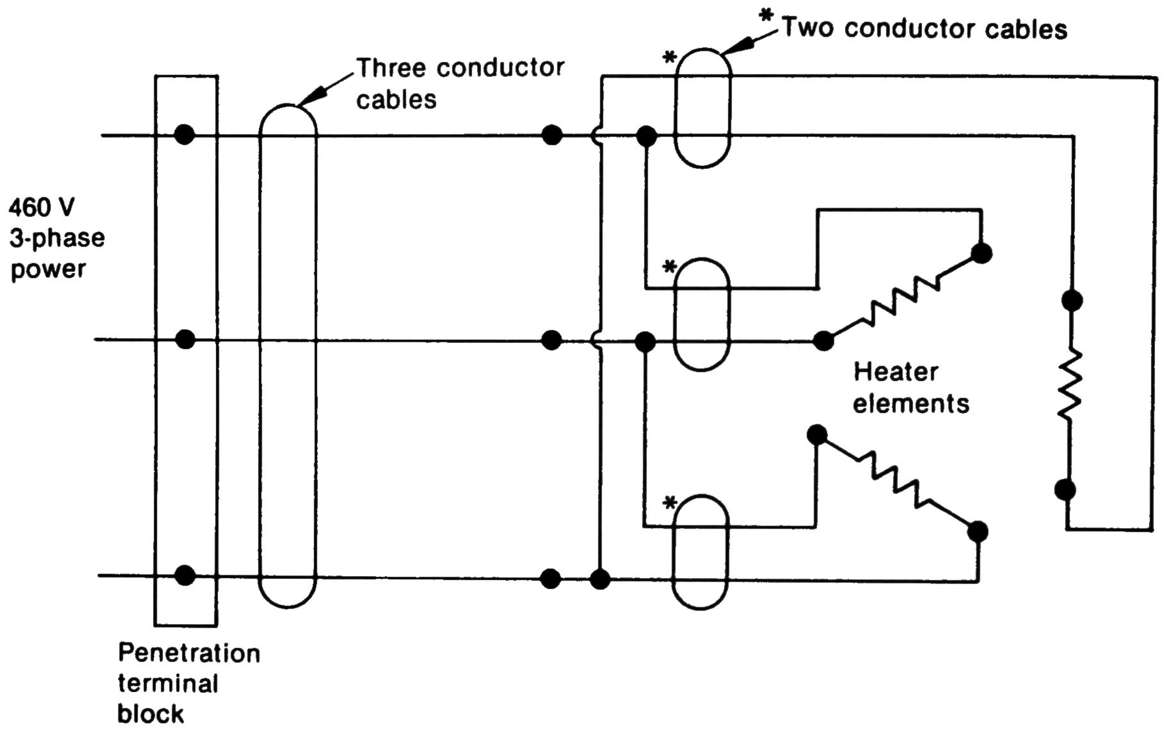


Figure 23. Typical wiring diagram for pressurizer heater circuits.

and showed deviations from the expected nominal power from -8.6 to +8.9%. This narrow range of deviation from expected nominal power indicates that these heaters are likely all functional although this range of deviation does not rule out the highly unlikely possibility that a heater element resistance is low and its connection resistance is equally high. This would give the possibility of an overheated connection.

As for other circuits, insulation resistance should have little effect on circuit operation because it is a measure of an abnormal current path. However, the very low insulation resistance of 22.5 ohms for S080P might prevent normal operation by either excessive ground fault current or a fire caused by excessive power dissipated through the low insulation resistance. This current would be interrupted by a ground fault detector. Functional problems for the pressurizer heater circuits are given in Table 11.

Current Transformers

Three cables connected to current transformers as shown in Figure 24 were measured. Loop resistance, inductance, and TDR measurements were made between the common and each of the other conductors. For cable H348C, the loop resistances were within the range expected for the cables alone indicating that the circuits were functional unless the current transformers were shorted. However, inductance measurements indicate that the current transformers were not shorted. TDR data show no indication of problems with circuits of this cable. Because the loop resistances are within expected values and no other problems were found, further calculations are not needed to show that these circuits are expected to be functional.

For H337C terminals TB1/1-4 and for H359C terminals TB1/7-10 have open circuits and therefore are not functional. TDR data shows each of these to be open at the penetration.

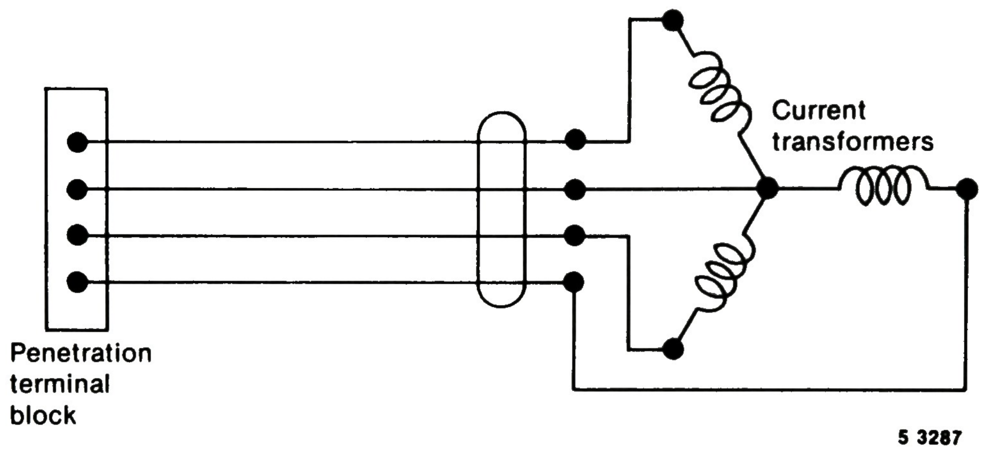


Figure 24. Typical wiring diagram for current transformer circuits.

Neutron Detectors

Because these detectors are unpowered, they look like open circuits at normal dc testing voltages. Therefore, any information about high loop resistance cannot be evaluated, however a few items can be checked. First, the capacitance measured can be analyzed and compared to the expected value for the cable alone (see Table 12). Table 12 shows that two cables measured about 1500 to 2000 pF more than expected for the cables alone, which seems reasonable; however, cable IT236C had only the capacitance expected for a 6.7-ft cable with no termination. The TDR data for IT2360C is shown in Figure 25 for comparison with that for IT2364I shown in Figure 26. The TDR response display for IT2364I would be expected from what is known about these circuits. Another similar cable, IT2362I, looks the same. The TDR response for IT2360C is compared to IT2364I to explain the lower-than-expected capacitance. The TDR display for IT2360C shows a slowly rising positive reflection just past the penetration. It also shows some response at the end of the cable. A small capacitive connection at the penetration will give the symptoms observed. The failure that would correlate with the TDR data showing the capacitive response is an open inner shield on the triaxial cable approximately 6 ft from the input.

In conclusion, IT2362I and IT2364I data do not indicate any functional problems. The data for circuit IT2360C indicate a problem, but the extent of the problem is not known without analyzing the output of the neutron detector. It is obvious from the TDR data that there is a communication path to the detector. Table 11 summarizes the neutron detector conditions.

Switches for Alarms and Annunciators

These are mechanical switches driven by sensors that are activated by pressure, temperature, level, or flow. Figure 27 is a simplified schematic for these circuits. Only the circuits with the switch contacts were measured.

TABLE 12. CABLE CAPACITANCES OF NEUTRON DETECTORS

Cable	Expected Cable Capacitance	Measured Capacitance of Cable Plus Termination
IT2360C	4.17 nF	0.11 nF
IT2362I	4.18 nF	5.69 nF
IT2364I	4.18 nF	6.10 nF

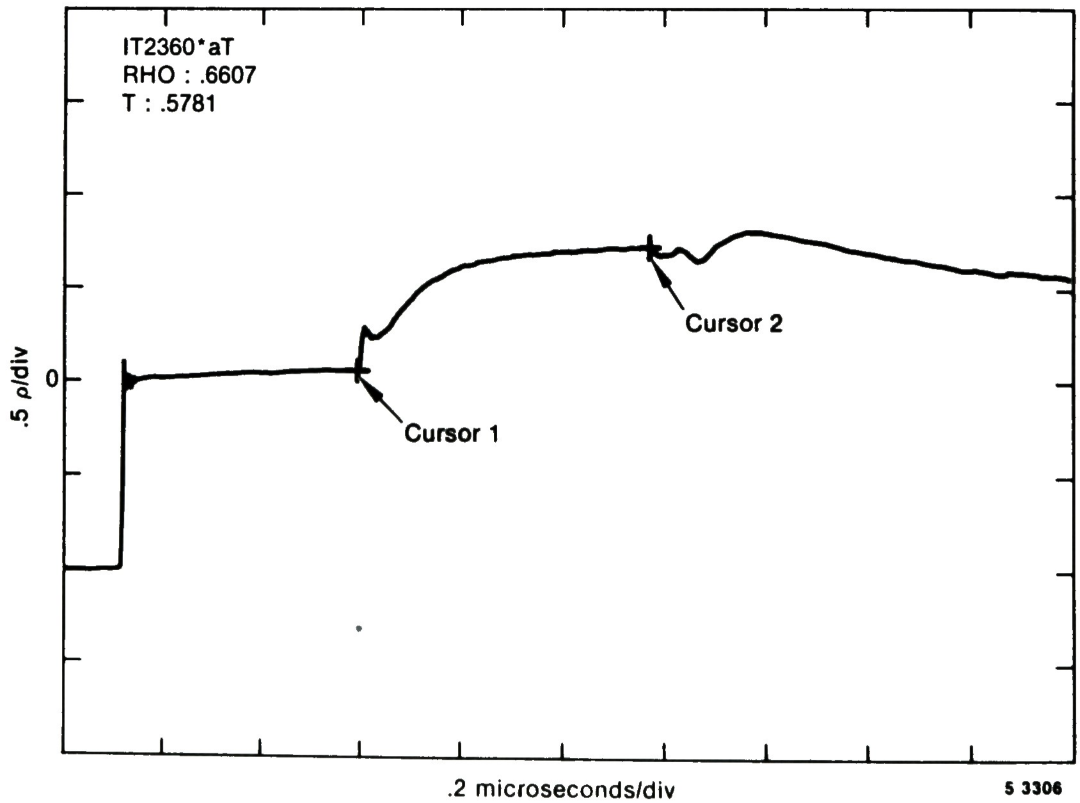


Figure 25. TDR display for cable IT2360C.

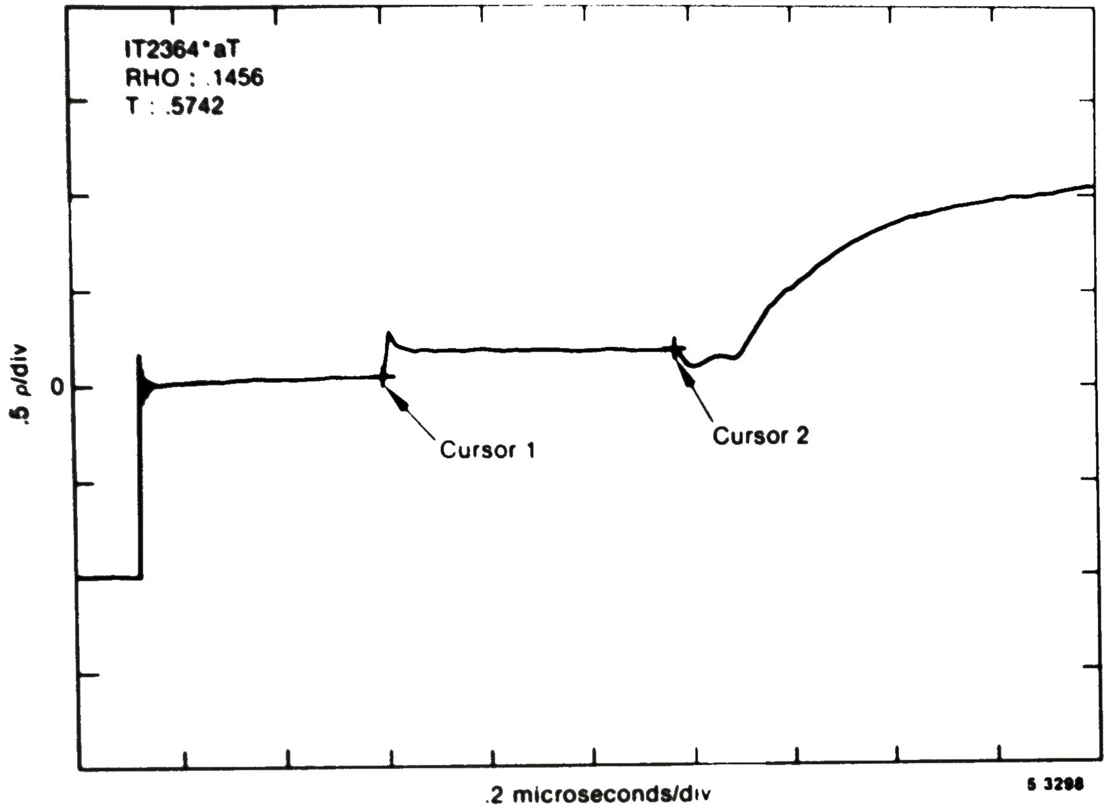


Figure 26. TDR display for cable IT2364I.

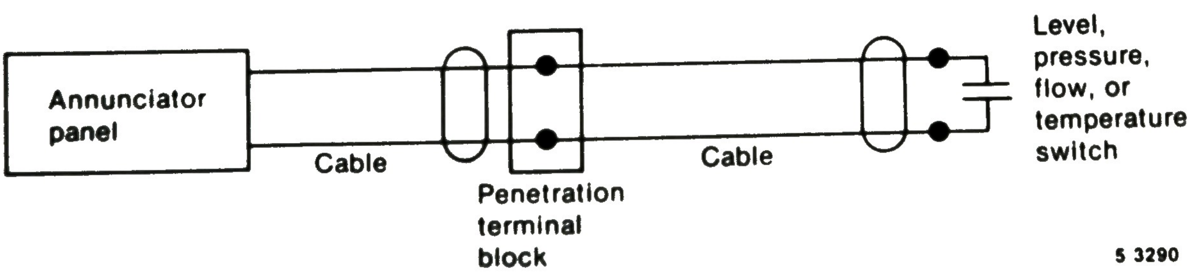


Figure 27. Simplified wiring diagram of alarm and annunciator circuits.

These circuits are driven by a Rochester Instrument Systems AN-1100 annunciator panel, which has an internal voltage source. The circuit current is equal to the voltage of the source divided by the total loop resistance, which includes the annunciator panel input resistance that is nominally 56k ohms. The manufacturer estimates that the current must be greater than 2 mA for normal operation. The source voltage is nominally 125 +/- 30 Volts, with the lower voltage occurring when loaded. Because of the fail-safe need at TMI, all switches are normally closed and give maximum loading. The minimum voltage would then be 95 Volts, and the input (loop) current for the annunciator would be 1.7 mA. Obviously, these limits are not realistic or the system wouldn't work, since 2 mA is the minimum input current for normal operation. Another approach will be taken to evaluate these circuits. Assume that an external loop resistance of 5% of the annunciator input resistance is a reasonable upper limit. This is 2.8k ohms, the upper limit for the circuit with closed contacts to function normally. To function normally a shunt or leakage resistance cannot deliver more than the 2 mA given above if the contacts are open. The worst case would be for the alarm voltage to be at its highest voltage. The minimum allowable circuit resistance for this case would be (155 V)/(2 mA), or 77.5k ohms. Subtracting the nominal 56k ohms input to the modules leaves 21.5k ohms external resistance. This is the lower limit for the circuit to function as an open circuit. The position of these switches was not specified. The following assumptions seem to be the best that can be made without further information: (a) if a loop resistance measures less than 2.8k ohms it is a functionally closed switch circuit, (b) if the loop resistance is greater than 2.8k ohms but less than 21.5k ohms, the circuit is nonfunctional, (c) if the loop resistance is greater than 21.5k ohms but not open it is a functionally open circuit, and (d) if the circuit measured open and the TDR showed the open at the end, then the cable is good and the circuit is likely to be functional.

Insulation resistance should have no effect on the operation of these circuits because it will not complete a circuit. Using the above assumption, no switch circuits were found to be nonfunctional.

CONCLUSIONS

One hundred forty four cables representing 20 cable types were tested from 10 various locations surrounding the reactor building. Cable types ranged in size from #4 gauge 3 conductor power cables to #18 gauge triax signal cables. Test locations at the penetrations varied from the 292-ft elevation azimuth 30 degrees to the 342-ft elevation azimuth 330 degrees. As a result, a fair representative cross section of cable types and test locations were encompassed during the phase of in situ testing.

Seventy eight circuits had anomalies that were identified from the in situ testing. It has been determined that the majority of the anomalies would not affect the functionality of the circuit. These circuits are, however, excellent candidates for future testing to study circuit degradation. Five circuits have been determined as nonfunctional.

Forty-four circuits had insulation resistance less than 10^6 ohms (see table 4) and two circuits had less than 30 ohms. 86% of the circuits with this type of anomaly were routed through the basement of the reactor building. The two circuits with insulation resistance less than 30 ohms are connected to the pressurizer heaters and are considered inoperative and hazardous if energized. Two current transformers have circuits which are open at the electrical penetration inside the reactor building. This penetration is located in the suspected direct steam path from the ruptured disc of the reactor coolant drain tank. Being in the steam path is believed to be a major contributor to this anomaly.

Ten circuits have high loop resistance values. However only one circuit is expected to be in-operative. This is due to an open in the pressurizer heater's delta windings. The other high loop resistance values are not expected to cause problems due to the nature of the circuits. These circuits contain switches or contacts that have operating ranges that will tolerate high resistance values.

Seventeen circuits in penetration R607 have TDR display anomalies that indicate water intrusion. The water level reached the centerline in this penetration. Each cable showing this type anomaly follows the same routing for approximately 50 ft. These anomalies are consistent on the TDR display for each cable.

Five circuits have high capacitance readings. Each of these circuits are connected to relay contacts or micro-switches within the D-ring. This high capacitance is most likely due to moisture at the end instrument.

Overall, the circuits with anomalies are routed through areas of known harsh environmental conditions. Those circuits that are considered nonfunctional were exposed to the most severe accident conditions. Thus, all anomalies are consistent with environmental conditions.

REFERENCES

1. H. J. Helbert et al, TMI-2 Cable/Connections Program FY-84 Status Report, GEND-INF-056, September 1984.

2. M. E. Yancey, Irradiation Test Report-- Foxboro E11GM, Bailey BY3X31A, and Flame Retardant Ethylene Propylene Instrumentation Cable, GEND-INF-058, August 1984.

3. M. R. Dinsel ltr to M. R. Donaldson, MRD-13-85, In Place Examination, February 12, 1985.

APPENDIX A

MOTOR STARTING VOLTAGE CALCULATIONS

APPENDIX A
MOTOR STARTING VOLTAGE CALCULATIONS

Because the data indicate that the motors were almost balanced electrically, the analysis used a balanced motor to vastly simplify computations. The voltages and currents shown in Figure 22 are given by

$$V_1 = V \sin \omega t$$

$$V_3 = V \sin (\omega t - 120)$$

$$I_1 = C_1 \sin (\omega t + \alpha)$$

$$I_a = C_2 \sin (\omega t + \beta)$$

$$I_c = I_a - I_1,$$

where α and β are the phase angles for I_1 and I_a, and C_1 and C_2 are the magnitudes of I_1 and I_a.

The motor impedance, $Z_m = R_m + j\omega L_m$ can also be expressed in vector notation as $Z_m = M_m \underline{/\theta}$, and the total impedance as $Z_x = R_s + R_m + j\omega L_m$, or expressed in vector notation as $Z_x = M_x \underline{/\phi}$ (see Figure 22). After writing the circuit equations and simplifying, the following were obtained:

$$V = C_1 R_s \cos \alpha + C_2 M_m \cos (\theta + \beta)$$

$$0 = C_1 R_s \sin \alpha + C_2 M_m \sin (\theta + \beta)$$

$$-0.5V = C_2 M_m \cos (\theta + \beta) - C_1 M_x \cos (\phi + \alpha)$$

$$-0.866V = C_2 M_m \sin (\theta + \beta) - C_1 M_x \sin (\phi + \alpha),$$

where V is the motor voltage at starting.

These equations were solved to find the value of R_s, which gave a motor voltage of 0.75V or $C_2M_m = 0.75$. Substituting this in the above equations, and letting $C_1R_s = gV$, where g relates C_1R_s to the starting voltage, gives the following:

$$\beta_2 = \cos^{-1}[(1.5625 - g^2) / 1.5]$$

$$\beta = \tan^{-1}[-.75 \sin \beta_2 / (1 - .75 \cos \beta_2)]$$

$$\alpha_2 = \tan^{-1}[(0.866 + 0.75 \sin \beta_2)/(0.5 + 0.75 \cos \beta_2)]$$

$$R_s = (\omega L_m / \tan (\alpha_2 - \alpha)) - R_m$$

$$g_x = (0.866 + 0.75 \sin \beta_2) / \sin \alpha_2$$

$$g = g_x R_s / M_x$$

$$\beta_2 = \theta + \beta$$

$$\alpha_2 = \phi + \alpha$$

where β_2, α_2, and g_x were constants introduced to simplify the equations.

When these were solved iteratively, values for R_s were found for each type of motor.

APPENDIX B

CHARACTERISTIC IMPEDANCE MEASUREMENTS

APPENDIX B
CHARACTERISTIC IMPEDANCE MEASUREMENTS

Cable characteristic impedance data were obtained from the TDR display. Figure B1 shows a TDR display for a cable in Penetration R607. The vertical scale is calibrated in reflection coefficient magnitude, which can be used to compute the cable characteristic impedance. This is done using two cursors, as shown. The TDR's Cursor 1 is placed on the level section, which corresponds to a 50-ohm section of cable that is used as an impedance reference. The TDR's Cursor 2 is placed at the end of the cable to be measured. This serves two purposes. The horizontal position is used to determine the cable length. The vertical position is a function of the cable characteristic impedance and can be used to compute a relative characteristic impedance from the values at Cursor 2 and Cursor 1. However, cable series losses cause this relative characteristic impedance to be somewhat in error. This is evidenced by the slight increase in reflection coefficient along the length of the cable, as can be seen in the figure. The correct value of characteristic impedance could be calculated if Cursor 2 could be placed at the start of the cable; however, because of reflections from the penetration this does not give good results.

The value of characteristic impedance can be found by fitting a theoretical curve to measured data over a portion of the cable near the end and as far toward the start of the cable as it is possible to find data not disturbed by reflections or other causes. Figure B2 shows the results of this curve fitted to TDR data from a long (about 200-ft) piece of RG-58A/U cable. The value of characteristic impedance obtained was 49.9 ohms. The specifications for this cable give the characteristic impedance as 50 ohms nominal; therefore, the value from the curve seems to be correct. The theoretical curve is based on a 50-ohm reference cable as were other TDR measurements as shown in Figure B1; hence, any errors in the reference cable are reproduced in the results. For the RG-58A/U measured, the characteristic impedance appears to be 60.2 ohms if calculated from the

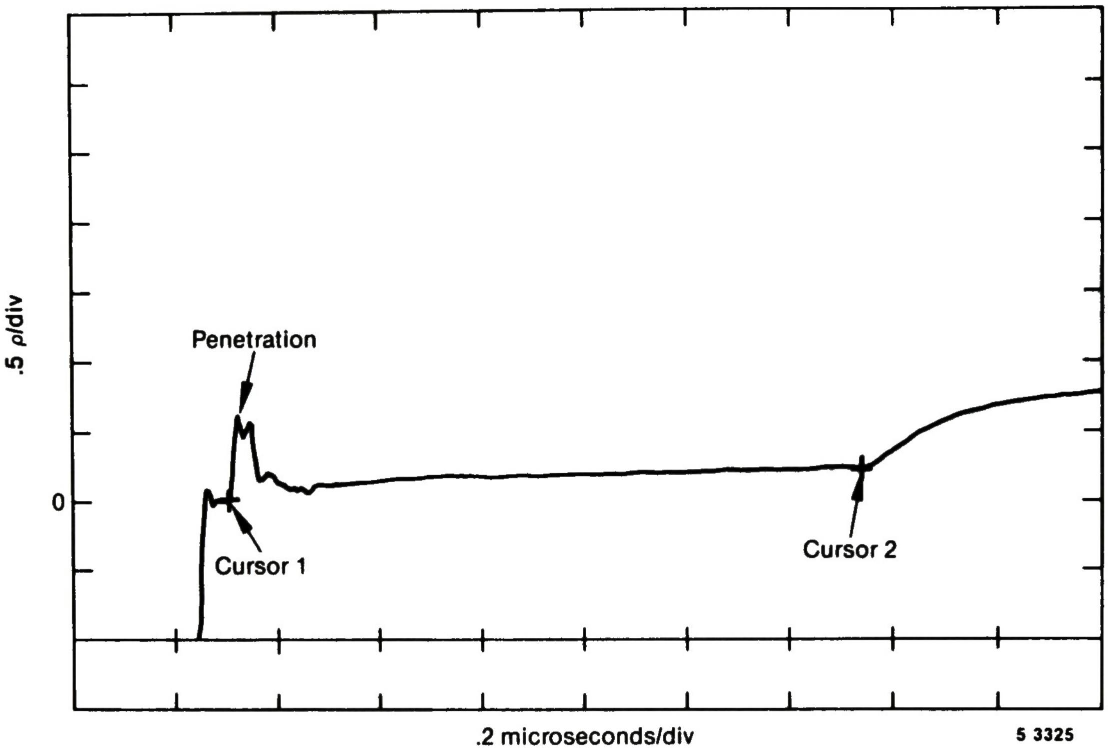


Figure B-1. Typical TDR display of a TMI-2 cable showing the cable penetration and two TDR cursor positions.

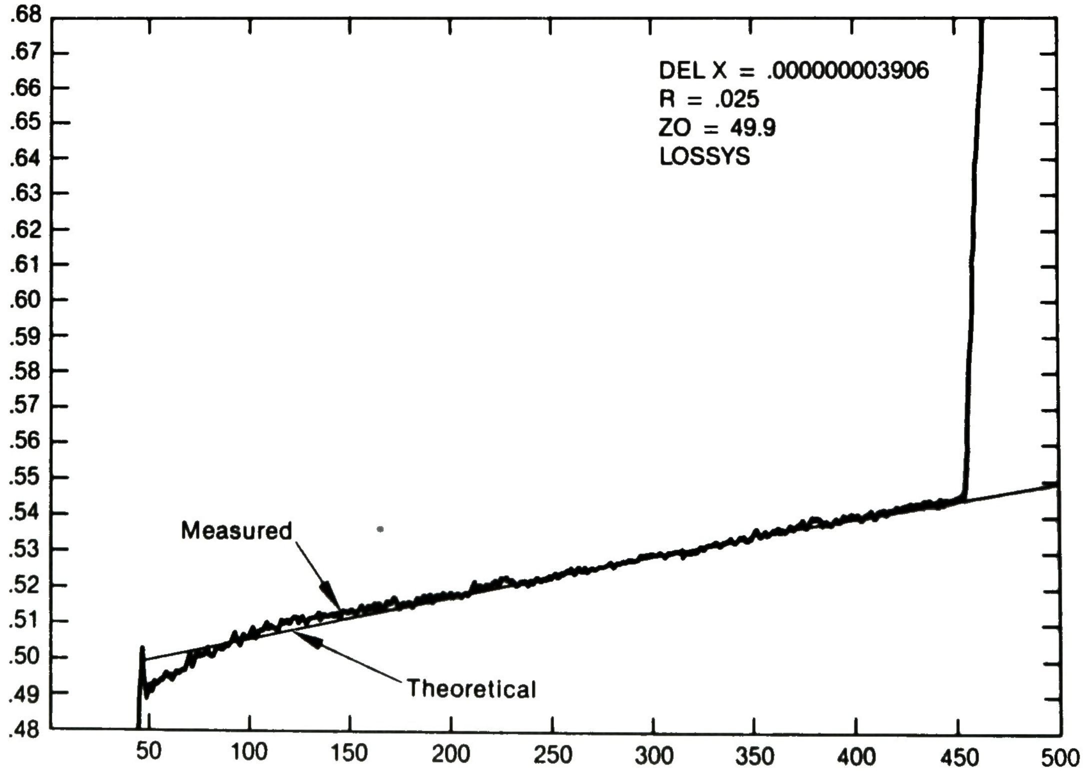


Figure B-2. Theoretical curve of reflected voltage fitted to a curve of measured reflected voltage.

reflection coefficient at the end of the cable. Notice that the theoretical curve fits the data very well over most of the length of the cable, but is noticeably different at the start of the cable. This has not been explained, but it is believed to be caused by a phenomenon not considered in the derivation of the theoretical curve. The theoretical curve was based on ideal cable, with only series resistance that did not vary with frequency. For real cables, the series resistance varies with frequency, noticeably at high frequencies. Whether this causes the error noticed in Figure B2 has not been determined.

The theoretical curve was tried on TMI data for several cables. Figure B3 shows the results for Cable/Connection IT2459/p-n. The characteristic impedance found using the theoretical curve was 65.1 ohms. Using the older method, the result is 77.0 ohms. The deviation between the measured data and the theoretical curve near the start of the cable appears to be similar to that observed for the RG-58A/U results. Figure B4 shows the results for another set of TMI data. All cables considered so far are believed to have losses predominantly caused by series resistance. Another type of loss is caused by equivalent shunt resistance, probably owing to dielectric losses. Figure B5 shows what is believed to be an example of this. The roughness of the measured data has not been explained but may be caused by the influence of metal external to, but very near, the cable. The difference between the measured data and the theoretical curve near the start of the cable seems to be opposite to previous examples. Figure B6 shows another example similar to Figure B5.

These examples show a method that should give more accurate measurement of cable characteristic impedance than previously used. The method had not been developed in time to be used for this report. With some refinement, it might be used for future analysis.

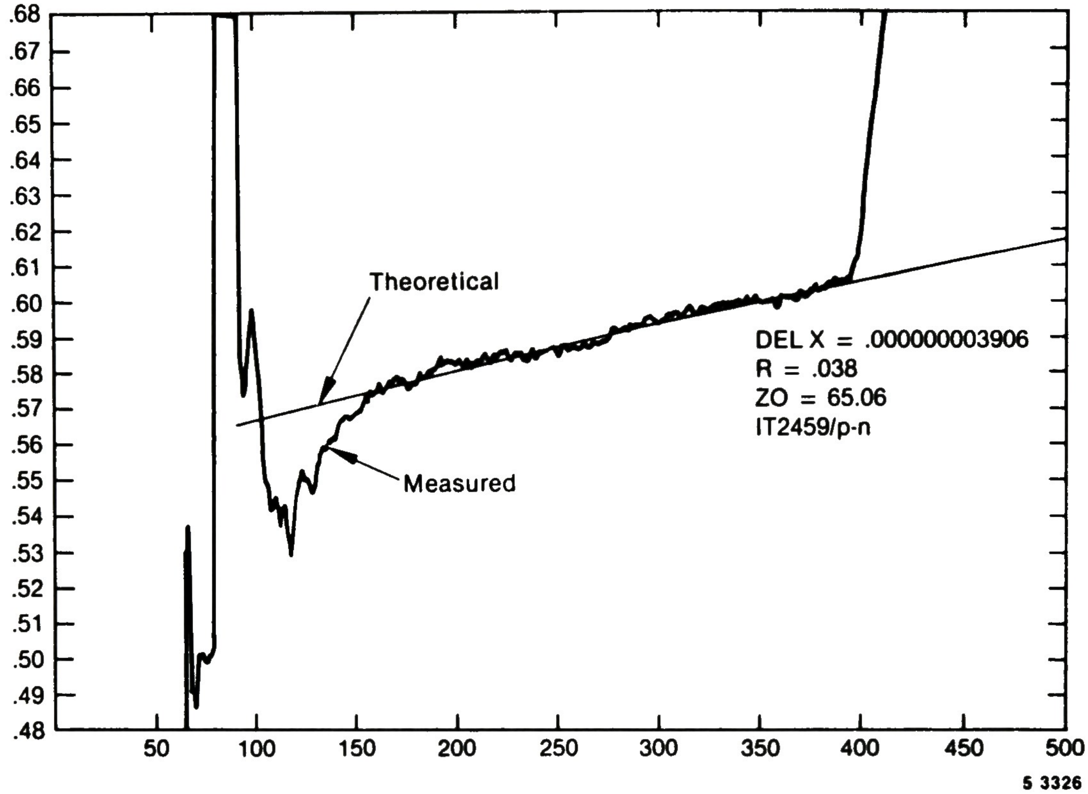


Figure B-3. Theoretical curve of reflected voltage fitted to the measured reflected voltage of cable IT2459.

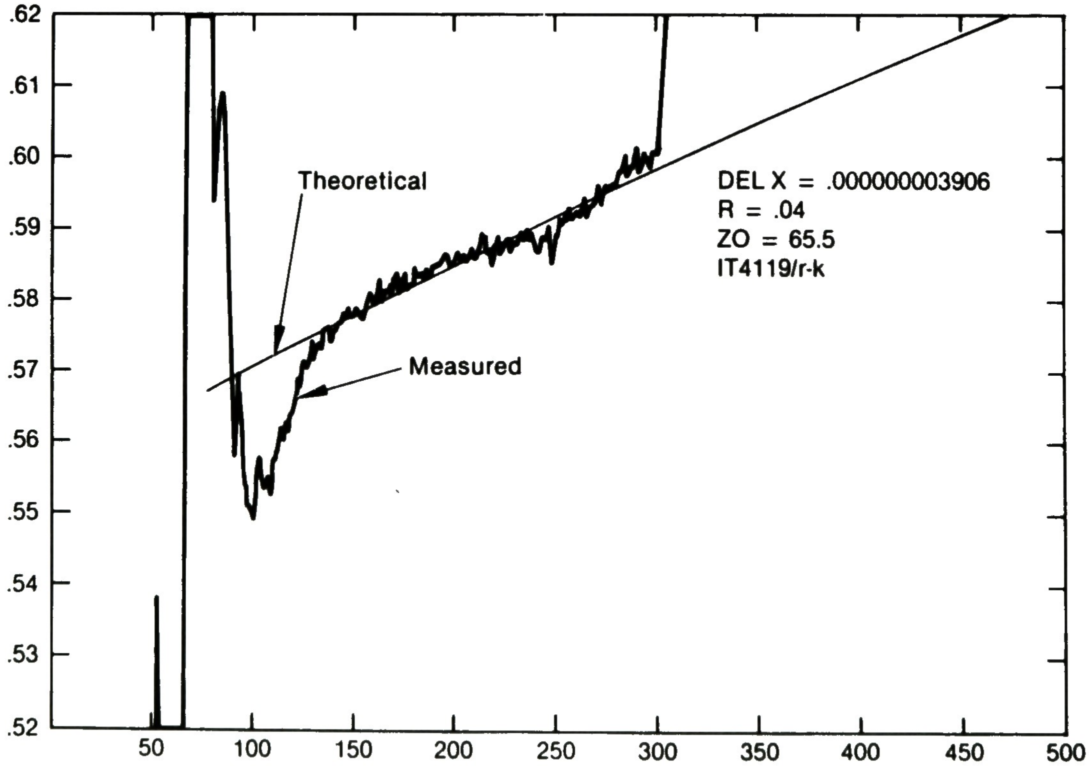


Figure B-4. Theoretical curve of reflected voltage fitted to the measured reflected voltage of cable IT4119.

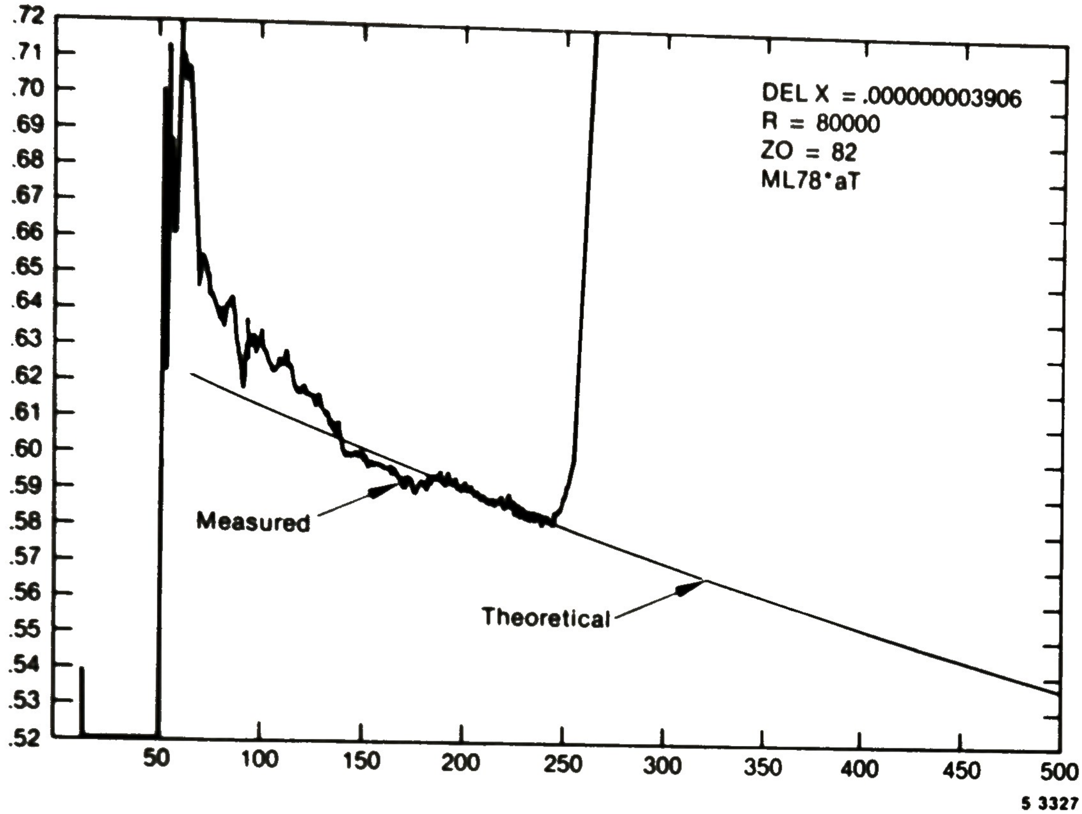


Figure B-5. Theoretical curve of reflected voltage fitted to the measured reflected voltage of cable ML78.

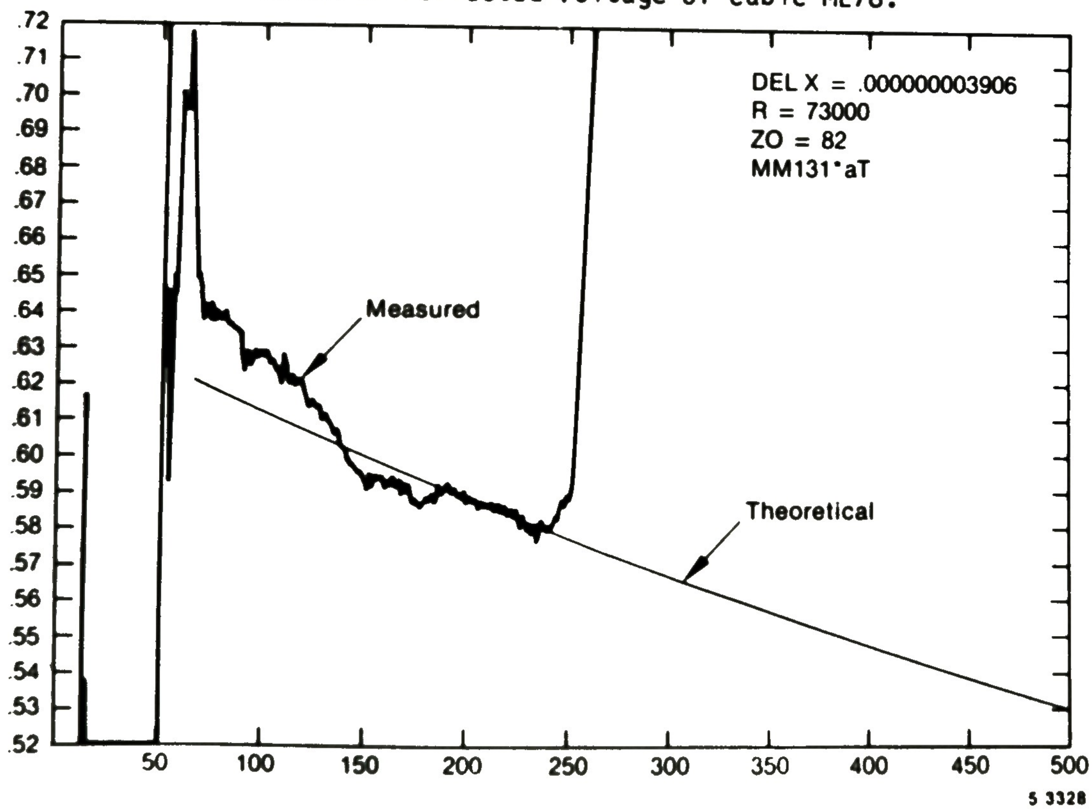


Figure B-6. Theoretical curve of reflected voltage fitted to the measured reflected voltage of cable MM131.